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Naval Open Architecture Machinery Control Systems for Next Generation Integrated Power Systems

Abstract

The Office of Naval Research has initiated the Compact Power Conversion Technologies Program (Compact Power) to speed the development of more compact/higher power density power conversion technology to support the long term goals of Next Generation Integrated Power Systems (NGIPS), and to progress the development of next generation power management controls to supervise the operation of these systems throughout the ship.

These next generation systems will require networked Compact Power conversion modules with agile embedded controls, which will participate in a multitude of prioritized local and distributed control strategies. These strategies range from converter control and system protection at the power interface level, to power quality and stability control with fault detection, isolation and recovery at the device level, and then up to mission-profile specific power distribution and reserve capacity alignment with flexible load planning and scheduling at the system level.

A collaborative product-line vision will drive the development of NGIPS and Compact Power controls, incorporating guidance regarding best practices and emerging standards-based technologies. Key elements in this vision include the IEEE 1676 guidance for high power electronic converters, the IEC 16850 process bus standard and other best-in-class and emerging technologies for Naval Open Architecture (NOA) Machinery Control Systems (MCSs). This paper discusses the driving forces behind and advancing vision of the emerging NOA MCS needed to support NGIPS.

Introduction

The need for agile power management and improved machinery control system software on naval ships is more important than ever given the diverse range of advanced sensors and weapon systems increasing the demand for electric power on both new ship platforms and legacy platforms being modernized. At the same time, the technology solutions for power management in the industrial automation industry and the commercial power utility industry are adapting to meet a host of emerging Smart Grid standards. This paper describes the state-of-the-art of control system technology applicable to Compact Power and NGIPS to help focus the development of embedded power conversion software and associated interfaces with the supervisory level applications as part of a future NOA MCS product-line vision. This vision includes the application of Smart Grid and Microgrid standards related to Power Electronics controls to address the integration of new power management software on future warships.

The paper begins with (1) a background discussion of NGIPS and the control system challenges it poses, followed by (2) a detailed discussion of best practices, emerging standards and emerging technology driving the vision for next generation machinery control systems. Finally, it provides (3) a more focused vision of how NOA MCS could be applied directly to the control system challenges of NGIPS, NGIPS Compact Power Conversion Modules, and NGIPS Power Management Controllers.

This paper also hopes to educate interested readers regarding state-of-the-art machinery control systems and to contribute to the process of developing outstanding machinery controls systems for NGIPS and other U.S. Navy applications.

NGIPS Background

Several independent factors have driven the evolution of naval surface ships towards larger power generation requirements and the use of electrical propulsion systems. These factors include:

- An increased need for energy efficiency, when operating in low to medium speed ranges,

- An increased need for power to support emerging high energy weapons and mission systems technologies,

- And many independent advantages of using an electrical drive system, including:

  - The ability to eliminate a great deal of heavy machinery, including reduction gears, shafting,

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and controllable pitch propellers,

o The ability to redistribute propulsion system machinery to improve space utilization and ship survivability,
o The ability to provide high levels of starting torque, useful for ice-breaking in cold seas,
o And the ability to use emerging podded propulsor systems to increase ship maneuverability and dynamic positioning capability, and to support advanced ship hull designs.

For both new ship classes and for the modernization of existing classes, these factors have driven ship designers to integrate their propulsion plant and electric plant together into a Next Generation Integrated Power System (NGIPS), which must operate under complex, interactive, mission-dependent real-time protection and control conditions and constraint.

The move toward NGIPS generates complex requirements for its Machinery Control System (MCS). These requirements range from hard real-time response requirements for equipment protection and control, to orchestrated distributed alignment requirements for changeovers in response to:

- Overall mission profile selections, establishing the NGIPS governing strategy for overall economy, perhaps during loitering or transit, or for maximum reserve power availability, during strategic engagement or combat,

- More specific power and propulsion profile selections, selecting generator and distribution alignments, rolling reserve targets and start and stop staging,

- Dynamically changing bridge lever commands, in response to pilot house orders,

- Dynamically changing ship loads, in response to mission and weapons systems and ship's crew activities,

- And in response to internally detected faults, which may require immediate fault isolation and controllable load reductions, followed by automatic reconfiguration and load recovery.

A short review of Integrated Power System basics will help to better illuminate these control system requirements.

Integrated Power System Basics

Integrated Power Systems consist of four general sets of components, as illustrated in Figure 1.
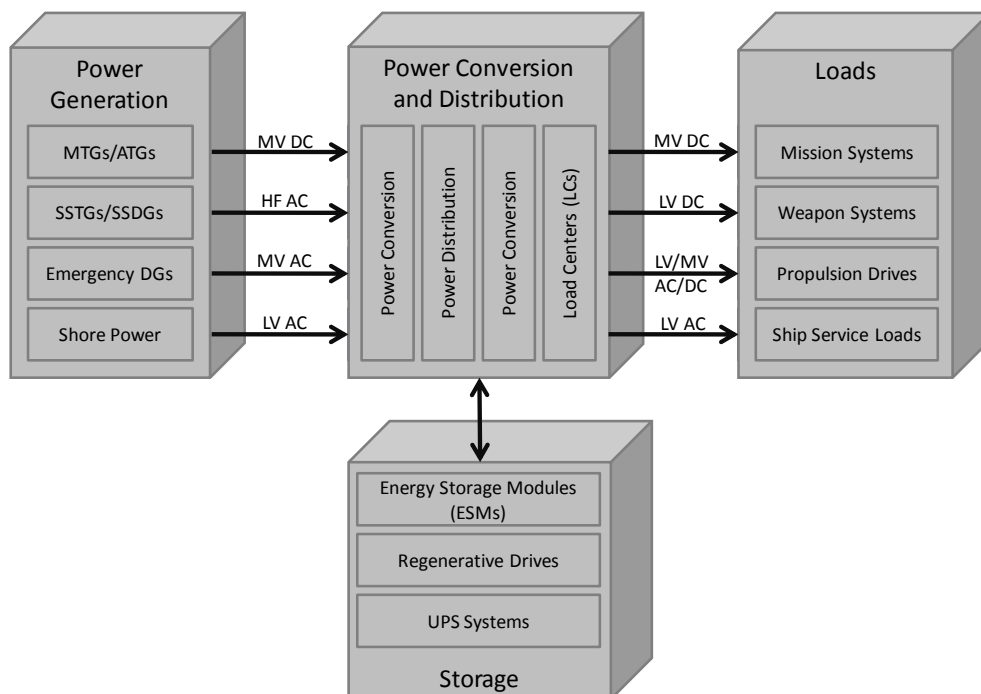

Figure 1: The Four Basic Sets of Components Comprising Integrated Power Systems

The first set of components is the Generator set, which typically consists of a prime mover, such as a diesel engine, gas turbine or steam turbine and its associated electrical generator. In ship's with dedicated propulsion equipment, the generator sets may only provide ship service power, and typically generate low voltage, 60 Hz, three phase, 450 VAC, but higher generator frequencies and voltages reduce equipment sizes and power distribution losses at constant power delivery. Consequently, current and next generation Integrated Power Systems may employ medium voltage (e.g. 4,160 V-13.8 kV) or higher frequency (200-400 Hz) generators[1].

The second set of components is the Conversion and Distribution set, which consists of switchboards and of power conversion and filtering equipment. Generator power is typically converted to one or more ship distribution levels, and then later converted to specific voltages, frequencies and quality levels needed by individual loads or load centers. In ship's with dedicated propulsion equipment, ship service designs often generate and distribute power at 450 VAC and 60 Hz, providing commonality with many building power systems. In order to improve power densities, designs are being driven to higher voltage and/or frequency levels, as previously discussed. In addition, new mission systems and propulsion drives have increased the variety of power delivery requirements for NGIPS. This has created the need for flexible power conversion modules that can source a wide variety of input power types and deliver a wide variety of load types.

The third set of components, the Loads set, includes the variable speed drives for the propulsion motors in the case of NGIPS. Many of the so-called "hotel" loads aboard ship consume power at standard power system levels: 450 VAC/60 Hz three phase, 220 VAC/60 Hz three phase, or 110 VAC/60 Hz. A variety of mission systems consume power at more unusual DC levels, while commercial variable speed drives for the propulsion motors typically consume power at either 450 VAC/60 Hz or 4,160-13,800VAC/60 Hz. Power is typically distributed to the propulsion drives at the highest available voltage, directly from generator switch boards with minimal conversion, to reduce the necessary size of and power losses associated with other conversion and distribution equipment.

The final set of components is the Storage set, whose components interact bi-directionally with the NGIPS, acting as a load when charging, spinning up or delivering power, and acting as a power source when discharging, spinning down, or regeneratively braking. Uninterruptable Power Supply (UPS) systems are the most common and traditional storage component, but other next generation energy storage module technologies are under development, which may be needed to support future missions and weapons systems. In addition, bidirectional variable speed drives that feed power back into the NGIPS when braking may also be used in future ship classes or modernizations.

Power Electronics as Building Blocks

As generator size and output power flexibility increases, and at the same time, as ship loads become more diverse and complex, power conversion becomes one of the key enabling technologies needed to support NGIPS. Fortunately, the emergence of high power electronic conversion modules has provided this key capability.

Electronic power converters play critical roles throughout the Navy's NGIPS vision. Traditional
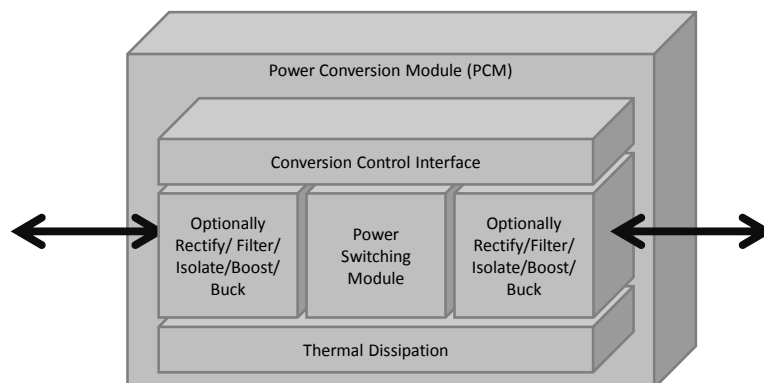

Figure 2: A Generic Power Conversion Module Block Diagram

methods of power conversion, including step-up and step-down transformers and rectifier bridge circuits, have been supplemented by the development of electronic switching module designs, which can perform DC-to-DC, DC-to-AC, AC-to-DC and AC-to-AC power conversion using power switching modules, as shown in Figure 2.

At the core of the converter lies the power switching module. The switching module turns transistors on and off at high frequencies at precise intervals in order to control the output wave form, voltage and frequency. When designing the converter, various types of power switching transistors are used based on the application's frequency, voltage and power requirements.

These modules typically rectify and stabilize incoming power into an internal DC form, and then re-chop the stabilized DC power into the output power using feedback controlled switch modulation control. Synchronized Pulse Width Modulation (SPWM) is a common technique used to generate AC output power synchronized to an external bus. The switching module actually generates fixed magnitude positive and negative pulses of varying width, which simulate a sinusoidal one or three phase AC wave form. Similarly, the switching module can employ pulse width modulated on-off "chopping" of the internal DC power source to feed Buck, Boost or Buck-Boost output circuits in order to generate DC output power at controlled voltage levels. When the converters must be bidirectional, the input sections must be able to rectify and stabilize power when it is flowing in, and must be able to perform controlled switching when the power is flowing out. Diodes are generally used to seamlessly change the behavior of the reversible section based on the instantaneous direction of power flow.

To enable the development of power electronic conversion modules for NGIPS and other programs, the U.S. Navy, through the Office of Naval Research (ONR), has co-sponsored the Advanced Electrical Power Systems (AEPS) program, previously known as the Power Electronic Building Blocks (PEBB) program[2]. ONR hopes to encourage the commercialization of standardized, affordable power conversion components that satisfy the requirements of both the commercial and the defense markets.

Key large volume commercial markets that use power electronic conversion modules include:

- Consumer and Office Electronics
  - Inverters (12/24 VDC to 115/220 VAC 60/50 Hz)
  - Power Supplies (115/220 VAC 50/60 Hz to 1.5-24 VDC)
  - Uninterruptable Power Supplies (UPS)

- Automobiles and Trucks
  - Electrical Drive Power Control Modules
  - Hybrid Electric Drive Power Control Modules

- Industrial and Commercial Power and Control Systems
  - Electronic Power Conditioners and Filters
  - Inverters (DC to AC, 1 or 3 Phase, 50/60/400 Hz)
  - Power Supplies (AC to DC, DC to DC)
  - Uninterruptable Power Supplies (Commercial and Facility UPS)
  - Variable Speed Drives (DC and AC to Variable Frequency AC)

- Marine Systems
  - Auxiliary Propulsor Drives
  - Variable Speed Auxiliary Drives
  - Variable Speed Propulsion Drives

- Alternative Power Generation/Microgrid Systems
  - Fuel Cell Systems (DC-to-AC systems)
  - Grid-Tied and Multiple Feed Inverters (DC-to-AC and AC-to-AC systems)
  - Hydro and Wind Turbines (Intermittent and variable frequency AC to AC converters)
  - Solar/Photovoltaic Power (DC-to-AC converters)

- Electric Utility Systems
  - Flexible AC Transmission Systems (FACTS)
  - Step-Up and Step-Down Converters for High Voltage Direct Current (HVDC) Transmission Systems

Zonal Electrical Distribution Systems

For NGIPS, multifunction electronic Power Conversion Modules (PCMs) are used to adapt ship service distribution systems to support higher power generation requirements and more diverse loads including propulsion, mission and weapons systems. In the past, electrical power distribution systems on U.S. Navy ships have always been designed to provide high reliability for vital loads, and more recent ship designs have utilized a Zonal Electrical Distribution System (ZEDS), to provide enhanced survivability during and after equipment casualties. For NGIPS, the zonal distribution model was adopted. Figure 3 illustrates a zonal distribution system, for discussion purposes[3].
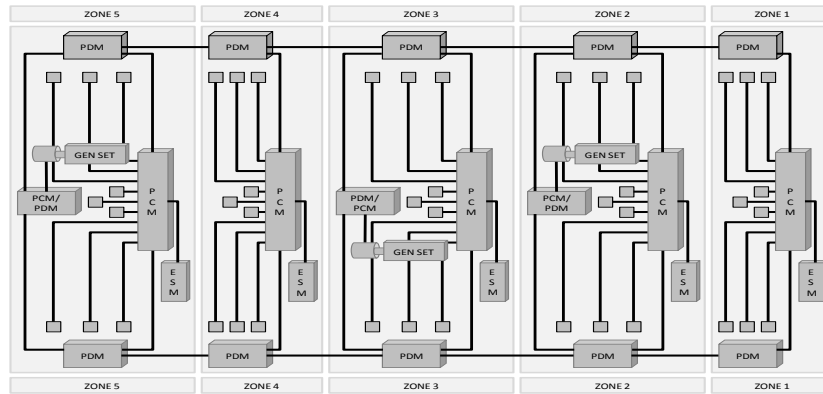
Figure 3: A Notional Zonal Electrical Distribution System

With zonal distribution, the ship is separated into distinct electrical distribution zones along existing watertight boundaries. The zones are inter-connected via two longitudinal power distribution busses, with one bus typically running along the starboard side of the ship, and the other bus typically running along the port side. Each zone can import or export power from adjacent zones on the longitudinal bus, or it can isolate itself from adjacent zones using its Power Distribution Module (PDM).

Zones that contain generator sets can also convert power to the distribution voltage, using a Power Conversion Module (PCM), and then feed power to either of the two longitudinal busses using a PDM. Some systems may also support cross-tying the busses using the generator PDM or using another PDM dedicated for this purpose.

In many designs, PDMs may simply be switchboards with their associated integrated controls, or they may be switchboard components integrated into a collocated PCM.

Within each zone, either in-zone or imported power received from the longitudinal busses is fed to one or more Power Conversion Modules (PCMs), to service vital and non-vital loads and load centers located throughout the zone. In addition, zones may contain Energy Storage Modules (ESMs), which store power and can provide emergency power during periods of power loss or unintended zone isolation. Typically, zones will contain several PCMs providing redundant sourcing for vital loads via Automatic Bus Transfer (ABT) switches or via DC auctioneering diodes. In addition, for some designs, the distribution modules may be integrated with
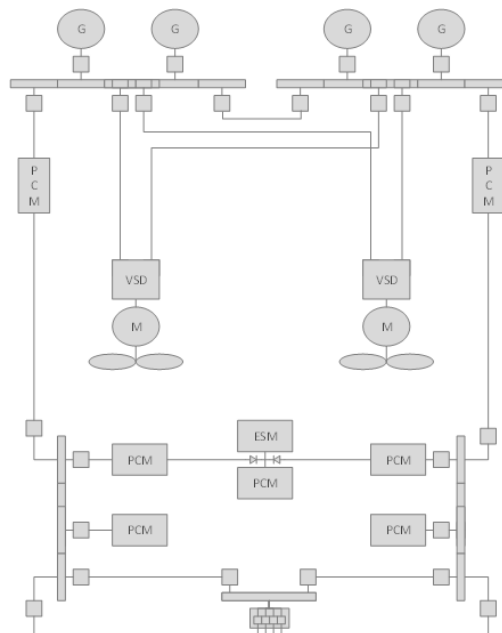

Figure 4: A Notional NGIPS One-Line Diagram

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the conversion modules.

When zonal distribution is combined into an Integrated Power System, the Main Propulsion Variable Speed Drives (VSDs) and Motors (M) become major loads that are often directly attached to the Generator (G) switchboards as shown in the form of an electrical one-line diagram, Figure 4.

This diagram separates the higher voltage generation and propulsion system from the rest of the ship service distribution system, and only depicts one distribution zone, which contains a shore power receptacle.

In some ways, the top portion of the diagram is analogous to a traditional propulsion plant, with the generator, variable speed drive, motor and fixed pitch propeller, replacing the traditional reduction gear, shafting and controllable pitch propeller. The electrical system also adds the benefits of (1) a cross-connect gearbox, allowing one prime mover to move both propellers, and (2) a reversing gear if the variable speed drive is reversible.

Future Directions and Control Challenges of Next Generation Systems

Traditional naval electric plant designs have borrowed extensively from products sold to commercial markets and from commercial ship designs to reduce Non-Recurring Engineering (NRE) costs and associated development risk. Generator sets and their controls that were similar in capacity and design to emergency diesel generators for buildings, such as hospitals, and split switchboard designs were very similar to designs used on commercial ships. NGIPS will move naval electric plant designs away from commercial building designs towards emerging Smart Grid Substation and Microgrid designs.

Also, traditional electric plants and propulsion plants operated more or less independently, and even operating independently, they still represented the two most complex machinery control systems aboard ship. With NGIPS, the electric plant and propulsion system become fully integrated, with the pilot house lever station directly raising and lowering electric power generation, and with the total capacity of the electric plant moving from the 2-to-10 MW hotel load range, to a 100 MW plus hotel-plus-propulsion load range. System capacities have moved from the high end of emergency generators, where three phase 450 VAC is common, to the low end of commercial electric power plants, where three phase 13.8 KVAC may be more common.

In addition, zonal distribution systems support a wide variety of sourcing and distribution alignment options, which facilitate the rapid reconfiguration and recovery of the system from equipment casualties. At the same time, however, this large number of permutations and combinations makes it absolutely necessary to thoroughly verify and test automatic fault detection, isolation and recovery strategies to ensure robust fight-through-power operations at sea.

Also, to ensure stability, traditional electric plants have used prioritized load shedding to maintain switchboard stability. With NGIPS, more advanced stability controls will be developed that take advantage of controllable loads, to provide less intrusive and more situationally aware power plant protection, but these more complex strategies will also need thorough verification and validation to ensure electric plant stability.

In addition, traditional mission and weapons systems seldom have a dramatic impact on the ship service power demand. Now, with emerging electromagnetic and laser based weapons systems, weapons systems power demand are expected to grow from the 500 kW range to levels in excess of 20 MW. This massive increase in power demand necessitates improvements in proactive, mission profile dependent, load planning.

Finally, NGIPS controls are needed to help optimize fuel consumption during peace keeping loitering and transit operations, when the ship is operating at low to medium speeds. Projected savings for operating the plant on fewer engines at a more efficient operating point can easily be squandered by choosing NGIPS configurations with too much power reserve.

In summary, the control challenges facing next generation systems include:

- Ensuring Safe Autonomous Operation throughout the NGIPS (Protection),
- Providing Fault-Tolerant Generation, Distribution, and Power Management (Fault Tolerance),
- Handling Unintentional Islanding and Overload Scenarios (Fault Detection, Isolation and Recovery),
- Supporting Mission Profile specific Distribution and Load scheduling (Source, Distribution and Load Management),
- Reducing Electrical Plant Operational Costs (Economy), and
- Creating a cost effective solution from a co-evolving set of OA equipment (Life Cycle Cost

Management).

Many of these topics will be covered in greater detail later in this paper.

NGIPS Machinery Control Summary

In summary, NGIPS will require a network of power distribution modules and compact high-power electronic conversion modules (Compact Power) with agile embedded controls participating in a multitude of prioritized local and distributed control strategies. These flexible PCM building blocks will play multiple roles in highly survivable NGIPS zonal distribution systems, and their roles in the system may often be integrated with the power distribution role for specific ship class designs.

In addition, interacting NGIPS control interfaces must be developed for PCMs and other participating equipment, including generator sets, Power Distribution Modules (PDMs), Energy Storage Modules (ESMs) and controllable loads. Furthermore, an overall, system level, power management distributed control application must be developed to provide overall coordination of NGIPS operations, including power source alignment and management, electrical distribution system alignment and management, controllable load planning and scheduling, and proactive mission profile specific supervisory control action.

The remainder of this paper will develop a collaborative product-line vision that will hopefully help drive the development of NGIPS and Compact Power machinery controls. The vision will incorporate guidance regarding applicable best practices, emerging standards, and other best-in-class and emerging technologies that will help create an enabling next generation Machinery Control System (MCS) to support the needs of NGIPS.

Vision Drivers - Best Practices

To develop a world class vision for next generation naval machinery control systems, we must start with current best practices for both machinery control systems and other closely related automation systems. The U.S. Navy and the U.S. Department of Defense provide proven guidance regarding best practices in this area, including three key practices that strongly impact the vision for machinery control systems. These three key practices are:

1. The application of "Naval Open Architecture (NOA)" principles, as prescribed by the U.S. Navy's Naval Open Architecture Enterprise Team[4],

2. The use of "Product Line Acquisition Strategies", as recommended by acquisition research investigations performed by Nickolas Guertin of the U.S. Navy's Program Executive Office for Integrated Warfare Systems (PEO IWS) along with Dr. Paul Clements of the Software Engineering Institute (SEI) at Carnegie Mellon University[5], and

3. The use of "Commonality-based" ship design and acquisition methods[6], as instructed by the Naval Sea Systems Command (NAVSEA) policy instruction for commonality of systems, subsystems, and components.

Each of the key practices is described in detail below.

Naval Open Architecture Principles

According to the "Naval Open Architecture Contract Guidebook for Program Managers"[7], Naval Open Architecture (NOA) is a combination of business and technical practices aimed at creating well architected, modular, portable and interoperable software systems based on open standards with published interfaces. When coupled with a well conceived modular design, the adoption of NOA principles offers the following advantages:

- NOA increases opportunities for innovation by enabling systems to interface with standards-based Commercial-Off-The-Shelf (COTS) products and components, as well as other Navy systems.

- NOA increases competition by ensuring inter-module interfaces within software systems are published and comply with open standards, allowing other competitors to interface with, replace or extend incumbent components, sub-systems, and systems.

- NOA increases opportunities for component, subsystem and system reuse, by encouraging modular designs based on standard published interfaces.

- NOA facilitates rapid technology refresh and insertion, by limiting component and subsystem coupling, and ensuring key interfaces are identified up front and are based on open published standards.

Historically, Machinery Control Systems have been slowly moving away from proprietary hardware,

networks, software and protocols toward a more open systems approach, but proprietary system configuration database schemas, proprietary inter-component application protocols, proprietary control application file formats, and proprietary Human Machine Interface (HMI) application file formats still severely limit Machinery Control System (MCS) application portability between vendor's systems. The selection and development of appropriate interface standards is key to improving MCS application reuse between ship classes for NGIPS.

Product Line Acquisition Strategies

The second key practice we will explore is the use of a product line acquisition strategy. The main advantage of developing and applying a product to serve a particular function for ship class delivery, over building a special turn-key system for ship class delivery, is that the product can be reused again for a different ship class, with little or no additional Non-Recurring Engineering (NRE).

This product development perspective is very common for the vendor community, but it may seem far less intuitive to view product and product line develop as an acquisition strategy. However, Nickolas Guertin of the U.S. Navy's Program Executive Office for Integrated Warfare Systems (PEO IWS) and Dr. Paul Clements of the Software Engineering Institute (SEI) at Carnegie Mellon University explored this paradigm shift, and concluded that a product line acquisition strategy was both (1) synergistic with Naval Open Architecture principles and (2) offered a major opportunity for cost reduction, quality and capability improvement and risk reduction for the delivery of Navy systems[8].

Guertin and Clements argued that the Navy should view all of the systems and subsystems they acquired that performed a specific function as products within product lines, which could and should be later reapplied across other ship classes (as they illustrate in Figure 5).

Guertin and Clements identified three key processes involved in the product line acquisition approach:

(1) CORE ASSETS: The reuse, refactoring, development or acquisition of core assets that are engineered for reuse (e.g. requirements documents, interface and interchange specifications, software component libraries and test tools, technical manual modules, reference designs, processes, management artifacts, ...),

(2) PRODUCTS: The development or acquisition of products that incorporate those re-usable core assets, and are also engineered for reuse, and

(3) PRODUCT MANAGEMENT: The ongoing management of a coordinated product development and delivery plan, which must evolve in scope as it supports specific ship class programs.

Two key questions should be asked when developing a product line acquisition strategy. The first is "What should the long term role be for the Navy?" and the second is "What should the long term role be for the suppliers?" These two questions are particularly of interest for Machinery Control System vendors.

Commonality-based Ship Design

The third and final key practice is the use of "Commonality-based" ship design and acquisition methods. As USN CDR Michael Cecere III, Jack Abbott, USN CDR Michael L. Bosworth, and Tracy Joseph Valsi described in their 1993 white paper, titled "Commonality-Based Naval Ship Design, Production &
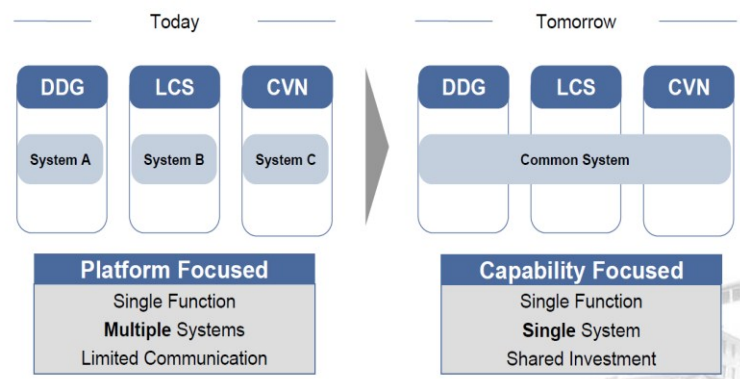

Figure 5: Acquisition Evolution Using a Product Line Strategy

Support"[10], for many years the Navy allowed individual shipyards to select modules and component parts to use in their ships (as illustrated on the left in the figure below). Competing shipyards did not collaborate when selecting component parts and modules, and as a consequence, a large number of very similar but different component parts and modules were used. This

Though a great deal of progress has been made, Machinery Control Systems (MCSs) continue to be a problematic area for commonality. Jeffrey Cohen of NAVSSES recently explored commonality in Naval Machinery Control Systems, and discovered that every surface ship class in the U.S. Navy had a unique MCS,
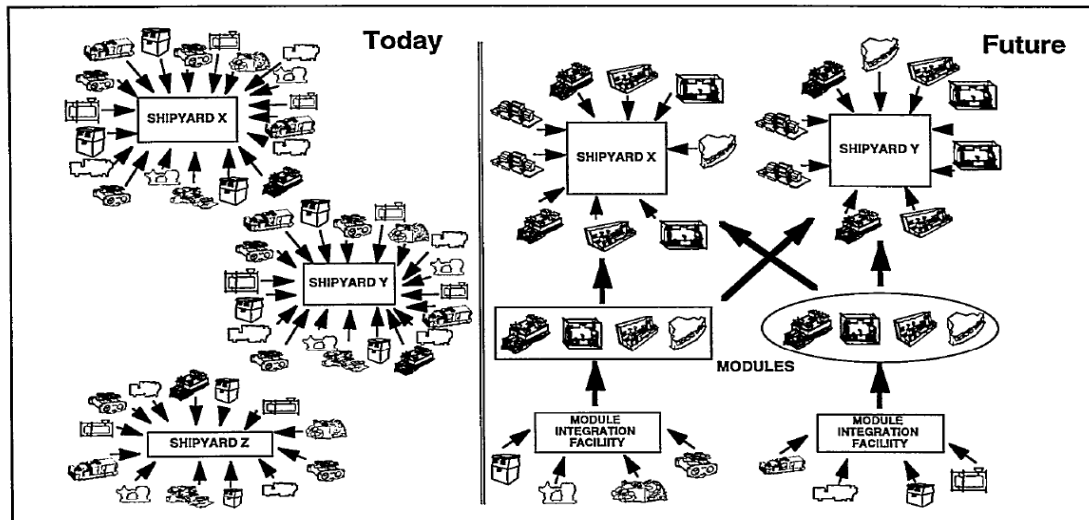

Figure 6: A Vision of Increased Commonality

unnecessary variation increased the Navy's costs throughout the ship's lifecycle, from design and production, to requirements validation, and finally to integrated logistics support.

The initial vision for increased commonality is shown above, on the left side of the figure. In this original vision, which is remarkably similar to the product line acquisition strategy, common modules that will be reused across ship classes are fabricated with common parts, reducing unnecessary variation, and eliminating replicated.

Since that time, the U.S. Navy's commonality efforts have grown. On April 6, 2009, Naval Sea Systems Command (NAVSEA) issued NAVSEA Instruction 4120.8, which established a "NAVSEA Policy for Commonality of Systems, Subsystems, and Components"[12]. This instruction established a Virtual Shelf concept along with requirements for its use. The Shelf has become an online database application that supports the selection of standard, proven components for use in new ship designs and modernization going forward, and has facilitated progress toward commonality.

and that some ship classes had different systems for different flights. Cohen concluded that "Non-standardization abounds", and that MCS commonality initiatives were warranted[13].

An analogy can be drawn between the current Naval MCS market situation, and the situation that existed in the computer market at the dawn of the Personal Computer (PC) era. Former Intel CEO Andrew Grove, in his book "Only the Paranoid Survive"[14], described this transition, as a shift from a vertically integrated proprietary computer system marketplace, to a new horizontal computer system marketplace enabled by the power of de-facto PC standards. To illustrate this transition, Grove provided an illustration where the computer industry was modeled as a set of 6 layers, labeled from bottom to top as:

SALES: **IBM**

APPLICATIONS: **IBM**

NETWORKS: **IBM**

OPERATING SYSTEMS: **IBM**

COMPUTERS:	IBM
CHIPS:	IBM

Grove explained that prior to the dawning of the PC era, each of the leading computer vendors, led by IBM, had vertically integrated, incompatible product lines, starting with their proprietary CPU chips, their proprietary computers, their proprietary operating systems, and moving on up to their dedicated sales forces. In addition, the market suffered from vendor lock-in; once you had purchased an IBM System 370 Main Frame or AS 400 Minicomputer, you were totally dependent on IBM for all your future needs and support.

Grove went on to explain, that with the introduction of the IBM PC and PC AT, including its completely open Industry Standard Architecture (ISA) reference design, and the introduction of alternative 8088/8086 and later 80286 and 80386 compatible processing chips, a new computer industry quickly arose, based on open, horizontal de-facto standards between each layer.

A multitude of manufacturers competed to make:

SALES: PC Computer and Software Stores
(Best Buy, Circuit City, CompUSA, Egghead,
SoftWarehouse ...)

APPLICATIONS: DOS and Windows application
software (Word Perfect/WinWord, Lotus 123/Excel,
Harvard Graphics/Powerpoint, DBase/Access ...)

NETWORKS: PC hardware compatible network cards
(Ethernet, Arcnet, Token-Ring ...)

OPERATING SYSTEMS: PC hardware compatible
operating systems (DOS, Windows, Linux, OS/2, QNX,
SCO Unix ...)

COMPUTERS: ISA compatible motherboards,
workstations and portables (Compaq, Dell, Gateway,
IBM, Osborne, Gateway, HP ...),

CHIPS: Intel x86 compatible processing chips
(Intel, AMD, IBM, NEC ...)
IBM's decision to develop the PC using other vendors off-the-shelf parts, then to publish the complete PC design including the ROM listing in its technical manual, and then to agree to terms with Microsoft that

didn't restrict them from licensing DOS to other parties changed the industry forever. The IBM PC reference design has remained the catalyst for a very competitive world-wide computer industry for over three decades now, and has provided an interesting template for the development and use of other detailed reference designs.

In many ways, the current Naval Machinery Control System market resembles the old vertical computer systems market of the late 70's. Once a Machinery Control System vendor is selected, only their system participates fully within the architecture, and there is a strong advantage for controlling the chosen platform, and for being the incumbent for modernizations (refer to the left side of Figure 7).

Still it is possible that the introduction of MCS module commonality along with appropriate standards-based interface specifications could drive a similar transition in the Naval Open Architecture Machinery Control System supplier market, like the right side of the figure above.

Within this new market, the Navy's Virtual Shelf becomes populated with Common Display Modules, Common Network Modules, Common Control Modules, in a variety of form factors, each with certified compatible replacement and upgrade paths available from multiple manufacturers. Software and communication interface standards allow portable display and control software from multiple vendors to seamless interoperate within one MCS, fully participating in the architecture, rather than being limited to some form of block data exchange. Both the MCS Framework software and the MCS HMI and Control Application software are portable and standards based, enabling complete reuse between platforms.

Vision Drivers - Emerging Electric Power Standards

The previous section of this paper discussed key best practices that should be applied to develop an outstanding vision for a Naval Machinery Control System for NGIPS. One of those key practices was to apply Naval Open Architecture principles, including the selection of applicable standards. Within the world-wide electrical power systems community, a massive set of changes is underway, called Smart Grid.

Domain	Actors in the Domain
Customers	The end users of electricity. May also generate, store, and manage the use of energy. Traditionally, three customer types are discussed, each with its own domain: residential, commercial, and industrial.
Markets	The operators and participants in electricity markets.
Service Providers	The organizations providing services to electrical customers and utilities.
Operations	The managers of the movement of electricity.
Bulk Generation	The generators of electricity in bulk quantities. May also store energy for later distribution.
Transmission	The carriers of bulk electricity over long distances. May also store and generate electricity.
Distribution	The distributors of electricity to and from customers. May also store and generate electricity.

Table 1

According to the National Institute of Standards and Technology (NIST)[15], power utility companies in the U. S. alone will spend $1.5-to-2 Trillion on Smart Grid related modernizations by the year 2030, or average nearly $100 Billion per year. The Smart Grid initiative involves seven distinct operating domains, and addresses both the flow of electricity and the flow of secure information between the domains[16](Table 1):

Of the seven distinct Smart Grid domains in the NIST reference model, only two are immediately relevant to NGIPS. They are:

- The "Customers" domain, which includes "Microgrid" related standards (IEEE 1547[17] and IEEE 2030[18]), which provide standards for the interconnection of Distributed Energy Resources to Electrical Power Systems,

- And the "Distribution" domain, which includes Substation automation standards (IEC 61850[19], IEC 62439-3[20] and IEEE 1588[21]), which provide standards for communication networks and systems in substations.
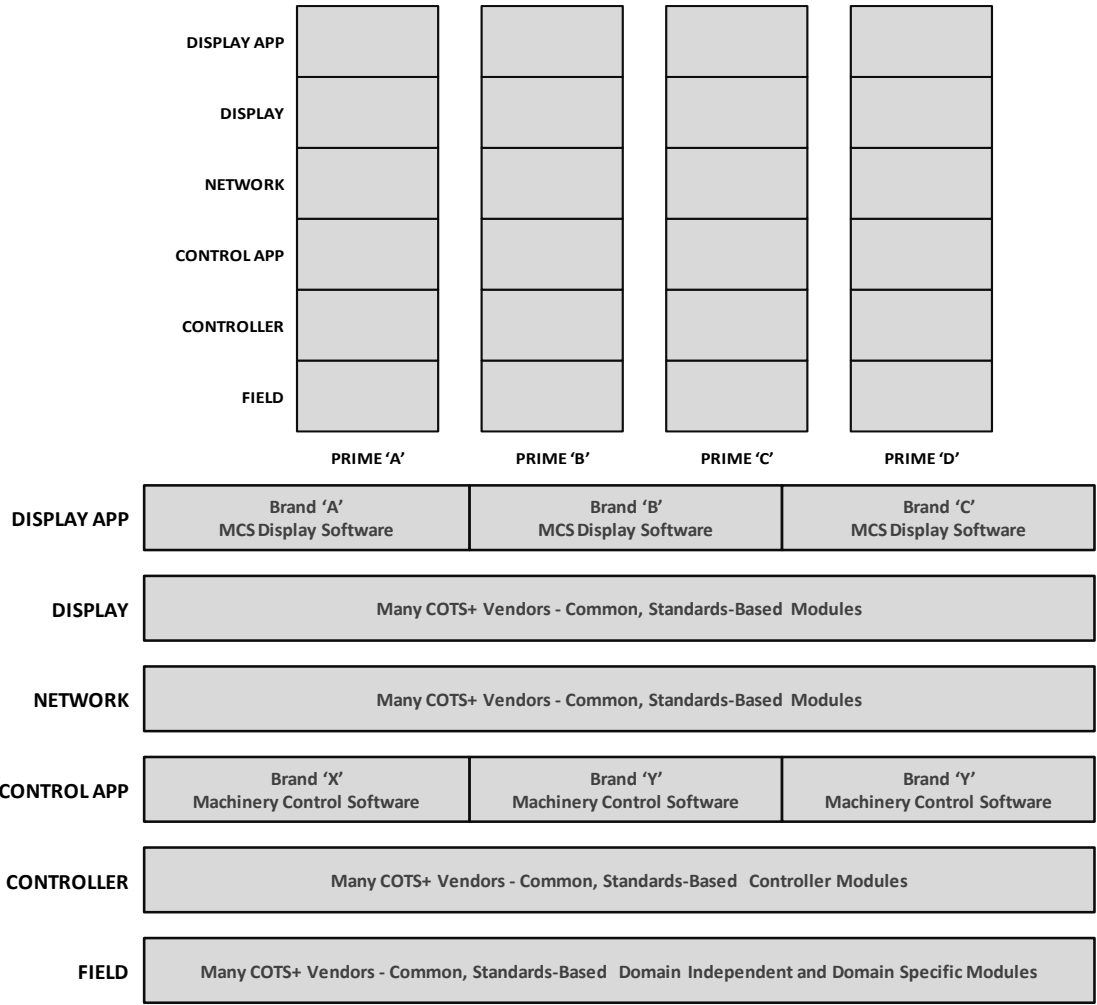

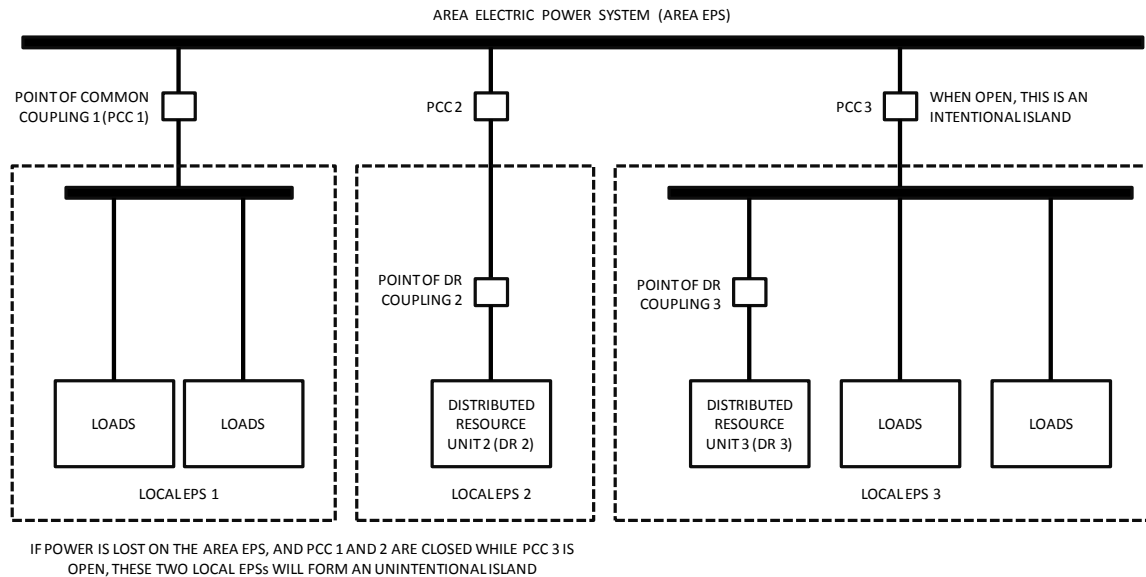Figure 7: A Possible Vertical to Horizontal Market Transition

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AREA ELECTRIC POWER SYSTEM (AREA EPS)

POINT OF COMMON COUPLING 1 (PCC 1)

PCC 2

PCC 3

WHEN OPEN, THIS IS AN INTENTIONAL ISLAND

POINT OF DR COUPLING 2

POINT OF DR COUPLING 3

LOADS

LOADS

DISTRIBUTED RESOURCE UNIT 2 (DR 2)

DISTRIBUTED RESOURCE UNIT 3 (DR 3)

LOADS

LOADS

LOCAL EPS 1

LOCAL EPS 2

LOCAL EPS 3

IF POWER IS LOST ON THE AREA EPS, AND PCC 1 AND 2 ARE CLOSED WHILE PCC 3 IS OPEN, THESE TWO LOCAL EPSs WILL FORM AN UNINTENTIONAL ISLAND

Figure 8: Topics Covered by IEEE 1547

These standards are already driving the development of new commercial products, such as multiple feed grid-tied inverters and switchgear control and protection devices that may become highly relevant to NGIPS in the near future.

Microgrid Standards

In the past, certain commercial buildings (such as hospitals) and manufacturing facilities (such as refineries or chemical plants) contained their own power generators for either emergency backup service or waste heat utilization, but these systems rarely had a major impact on the overall design of electrical power systems, in general. However, with the growth of distributed renewable energy resources, such as photovoltaic/solar systems and wind and hydrodynamic power turbine systems, and also with the development of laws requiring utility companies to allow integration of these systems with their regional electrical power systems, a newly emerging electrical grid of incumbent electrical power systems and interconnected distributed electrical power resources has evolved.

As part of the effort to enable this evolution, the IEEE Standards Coordinating Committee 21 on Fuel Cells, Photovoltaics, Dispersed Generation and Energy Storage has developed the IEEE 1547 Standard, illustrated in Figure 8.

The standard provides design guidance and detailed technical specifications and requirements for the interconnection of Local Electrical Power Systems (Local EPSs) to an Area Electric Power System (Area EPS) via a Point of Common Coupling (PCC) and any associated points of Distributed Resource (DR) coupling.

General interconnection requirements covered for DR coupling include:

- Frequency and Phase Synchronization,
- Voltage Regulation,
- Power Quality,
- Grounding Integration,
- Monitoring, Protection and Isolation, and
- Responses to Abnormal Conditions.

The standard also covers the concepts of Intentional and Unintentional Islands, as further described in the figure above. Local EPS 3 is an Intentional Island that contains DRs and loads, and can operate in isolation from the Area EPS. In addition, DRs in one Local EPS may become the only source of power for other Local EPSs, in the event of a power loss on an Area EPS. The standard refers to this as an Unintentional Island. Advanced campus and facility designs incorporating Intentional Islands, are also commonly referred to as Microgrids.

The standard is of interest to NGIPS for a variety of reasons. First, NGIPS can be thought of as a set of separate Local EPSs, one per zone, redundantly interconnected to an Area EPS via the longitudinal busses. Alternatively, NGIPS can be thought of as a

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complex Microgrid that is periodically interconnected to the Area EPS via Shore Power breakers. For both cases, the standard helps provide well researched specifications and requirements for associated system control and protection devices.

Second, the standard offers an evolving set of industry standards that will drive the design of many commercial products. In particular, the standard addresses requirements for the "Interconnection System" (see Figure 9), which may be a conventional generator set controller, with associated speed governors, voltage regulators, synchronizers and power control breakers, or may be a grid-tied power electronics based inverter, for a solar panel system with an energy storage module.
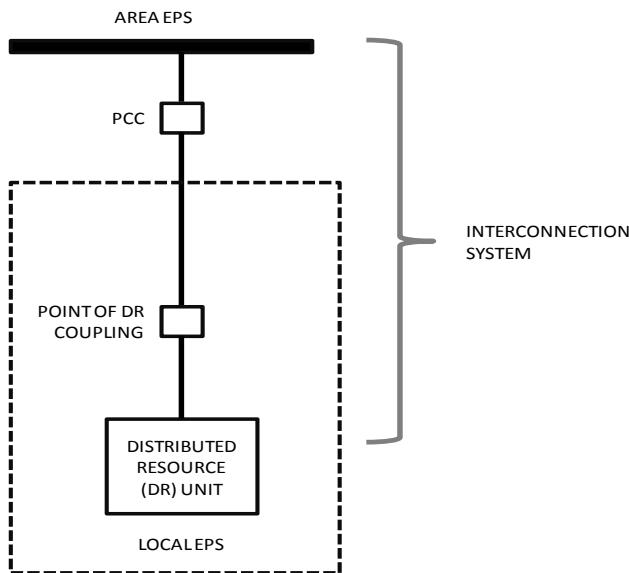
Figure 9: IEEE 1547 Addresses Grid Interconnection Requirements

In particular, *IEEE Standard 1547-4-2011 - IEEE Guide for Design, Operation and Integration of Distributed Resource Island Systems with Electric Power Systems*[24], is of particular interest to NGIPS. The standard addresses many special considerations, unique to island systems, including:

- Requirements dependent upon the current direction of power flow,
- The use of multiple Points of Common Coupling ,
- Reserve margin and load flow stability requirements when importing or exporting,

- The handling of transitions between various island modes:
  1. Area EPS-connected mode,
  2. Intentional/Unintentional transitions to Island mode,
  3. Island mode detection and operation,
  4. Reconnection mode, when operating in the correct voltage, frequency and phase angle windows.

For those of you familiar with naval electric plant operations, these operating modes may sound very familiar to many standard naval operations, such as 1. Shore power-connected mode, 2. Ship's power modes with switchboards tied or isolated, 3. Power loss detection, isolation and recovery, and 4. Resynchronization for transitions back to shore power or back to tied switchboards.

In addition to IEEE 1547, *IEEE 2030-2011 - IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads*[25] provides architectural perspectives and reference models for the development of system interoperability requirements for Smart Grid-related projects, including those involving Microgrids. The three Interoperability Architecture Perspectives (IAP) are the Power System IAP (PS-IAP), the Communications Technology IAP (CT-IAP), and the Information Technology IAP (IT-IAP). These three perspectives are used in conjunction with specific Smart Grid reference models to provide a detailed and common set of identifiers for power, communication and data flow paths within the system with associated tools and maps. Though the methodology carries a steep learning curve, it may mature into a very valuable framework for NGIPS.

Substation Automation Standards

In addition to the Smart Grid efforts to safely and reliably integrate distributed electrical power resources into existing utility grids to allow expansion of and innovation within the renewable and smart consumer energy system segments, there are also efforts aimed at improving the grid's reliability and fault isolation capability. For these purposes, substation modernization is a key focus area.
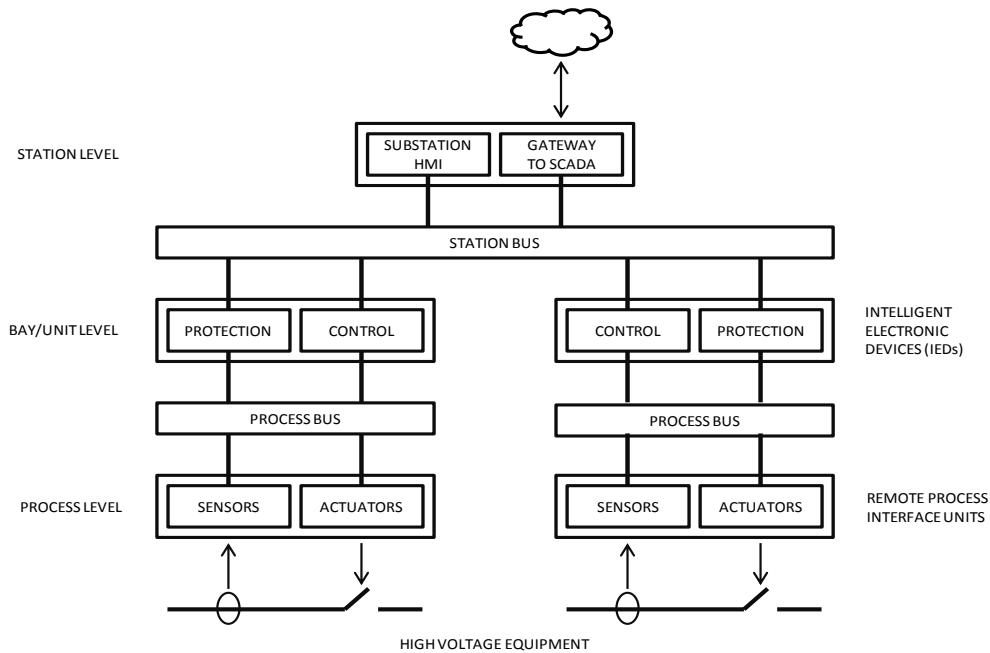
Figure 10: IEC 61850 Substation Automation Reference Model

Within the electrical power system, distribution substations receive incoming power feeds from one or more transmission lines, convert the power from transmission levels to distribution levels, and then feed the power to one or more distribution lines. Similarly, transmission substations, receive power from one or more incoming transmission lines, optionally convert the power to a different transmission level, and then feed one or more outgoing transmission lines. Substations may also contain large banks of capacitors that can be used to perform power factor control to reduce transmission line losses, and substations normally contain switchgear, which is a name given to large electrical disconnect switches that are designed to rapidly extinguish electrical arcs when they are opened. More relevantly, substations also provide fault detection and isolation capabilities that must occur as fast as possible to prevent cascading fault propagation to adjacent parts of the grid.

The Smart Grid committees developed the IEC 61850 standard, titled, "Communication networks and systems in substations", to drive the modernization of electrical substations to improve the fault detection, isolation, external notification and diagnostic identification capabilities of their control systems[26]. The standard introduced a new substation automation reference model, as illustrated in Figure 10.

The bottom of the figure represents the process level interface to the high voltage electrical power system equipment in the switchyard, including current and voltage transformers and switchgear. In the past, this equipment would be integrated with protection and control power relays in control bays inside a control building protected from the switchyard. IEC 61850 prescribes the development of a dedicated IEC 61850 "Process Bus", which is a new high performance network architecture that eliminates control relay wiring, and replaces it with a high bandwidth fiber optic network based on switched Ethernet technology.

With IEC 61850, the power relay equipment is replaced by IEC 61850 compatible Intelligent Electronic Devices (IEDs) that perform protection, control, monitoring, notification and recording activities, based to meet the goals of Smart Grid.

For NGIPS the key areas of interest are:

- New IEC 61850 "Process Bus" sensors, actuators and merging units (gateway devices that allow legacy sensors to communicate with the bus),

- New IEC 61850 "Process Bus" communication switches that implement new high availability Ethernet communication schemes,

- New IEC 61850 Intelligent Electronic Devices (IEDs), including protection, control and first-out recording devices,

- A suite of standards based communication protocols, including protocols introduced by IEC
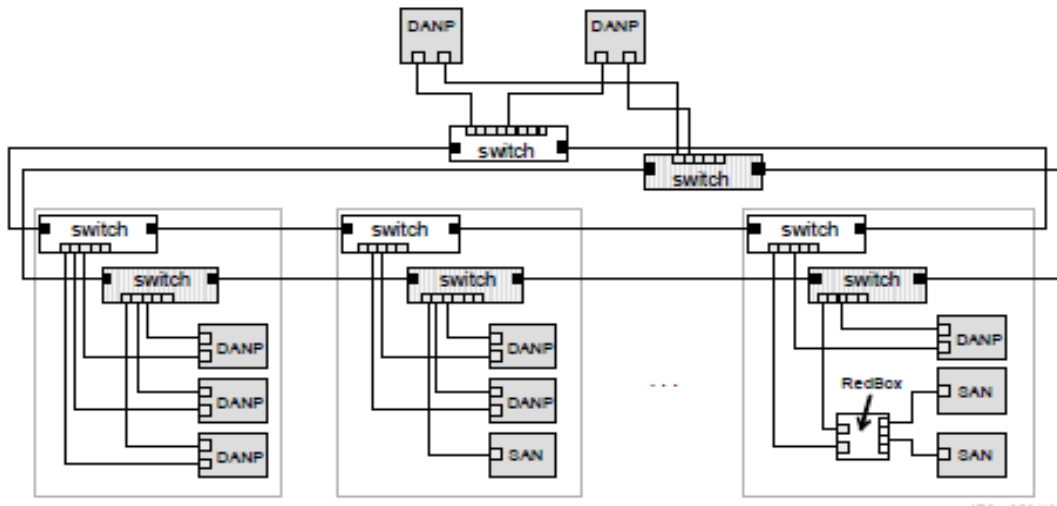
Figure 11: IEC 62439-3 Clause 4 - Parallel Redundancy Protocol

61850, and those adopted from other IEEE and IEC standards.

In particular, the emerging "Process Bus" communications standards are of special interest, and we will delve into them in greater depth.

High Availability Automation Networks Standards

The availability and performance requirements needed for substation process control and protection drove the development of two new high availability automation networks based on fiber-optic switched Ethernet base technology. The two new high availability standards were developed by consortium and standardized as *IEC 62439-3 - Industrial communication networks - High availability automation networks - Part 3: Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR)*[28]. The first of these standards, Parallel Redundancy Protocol, is illustrated in Figure 11.

The PRP design is similar to the redundant networking design used by many existing dual-homed machinery control systems: each node in the system is attached to two independent physical networks, so faults and spanning tree events on one network do not influence the other network. The difference between PRP and dual homed networks is that PRP provides the redundant networking transparently at the network interface card driver layer, while typical machinery control systems provide the redundancy non-transparently, by employing two separate IP (Internet Protocol) addresses.

The transparent redundancy support simplifies the network implementation, and it also allows simple sensor devices that may not be capable of supporting a TCP/IP (Transmission Control Protocol/Internet Protocol) stack to support PRP redundancy. In addition, the PRP design takes advantage of certain switch layer QoS (Quality of Service) extensions to ensure hard real-time performance. These features were key design objectives for the "Process Bus", as we will discuss later when we look at the IEC 61850 Sampled Value (SV) and Time Synchronization protocols.

In the figure, DANP stands for Doubly Attached Node using PRP, and SAN stands for Singly Attached Node. Note that the PRP network can support some nodes that are singly attached to the network switches, and it can also support a so-called "Red Box" that allows singly attached nodes to support redundancy in a gateway fashion. The first method is useful for maintenance connections, while the second method is useful for legacy devices.

The second new high availability automation network standard was High-Availability Seamless Redundancy, or HSR, as shown in Figure 12.

Though HSR was designed to support several topologies, the seamless redundant ring topology is the one most commonly employed. The primary advantage of HSR over PRP is that it does not require infrastructure switches; its primary disadvantages are that it doesn't scale as well as PRP and it loses its fault tolerance after one node failure. With HSR, Doubly Attached Nodes using HSR (DANH) form a physical ring and messages
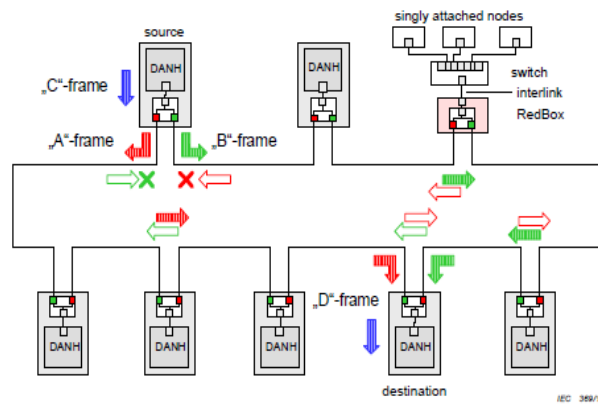
Figure 12: IEC 62439-3 Clause 5 - High-Availability Seamless Redundancy (HSR)

are sent in two directions by transmitting nodes. A similar "Red Box" gateway node is provided in the design to support Singly Attached Nodes (SANs).

The switchless HSR approach may have advantages for small networks like those envisioned for single-bay IEC 61850 "Process Bus" solutions, but PRP networks will likely turn out to be more adaptable to other control applications. The technologies will likely compete for a while, before one emerges as a long term winner.

For NGIPS, these high-availability real-time control networks are of interest in the design of Power Conversion Modules (PCMs), Power Distribution Modules (PDMs), and even may become a preferred solution for the machinery control system network itself. Currently, prior to IEC 61850, smart/numerical circuit breakers typically had integrated sensor interfaces, were externally controlled using digital signals, and provided

monitoring information through a serial or network interfaces, using standard industrial protocols. With the advent of IEC 61850 "Process Bus" the sensor data can be monitored and controlled in real-time across the bus, with latency times below the stated target value of 4 milliseconds, which is as good as or better than those achievable with protective power relays.

Substation Automation Protocols

In addition to driving the development of the "Process Bus", the IEC 61850 standard also specified a diverse protocol suite to handle a variety of Smart Grid related problems. The IEC 61850 protocols are summarized in Figure 13.

IEC 61850 specifies two real-time communication protocols to support the "Process Bus": Sampled Values
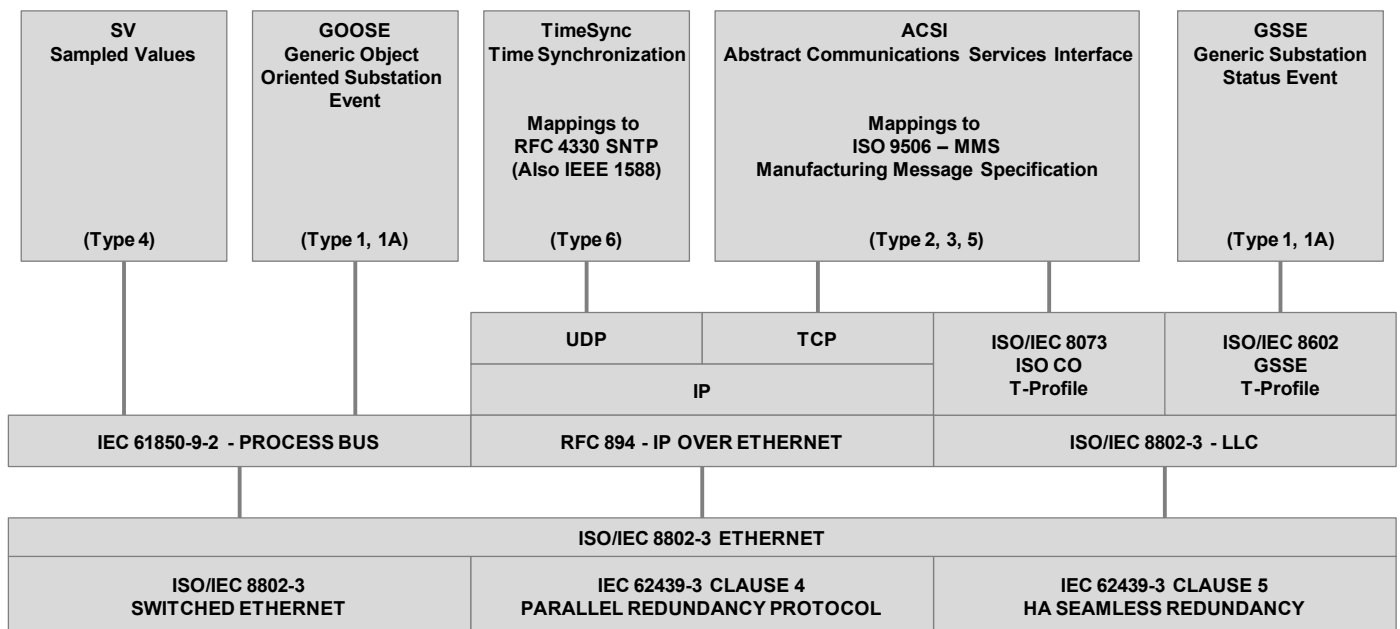

Figure 13: IEC 61850 Substation Protocol Summary

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(SV) and Generic Object-Oriented Substation Events (GOOSEs). With SV, sensors attached to the process bus multicast their values isochronously using real-time QoS extensions. The design of the SV protocol supports sampling rates that would allow some forms of remote wave form analysis as well as RMS (Root Mean Square) current and voltage determinations.

The GOOSE protocol is designed to provide rapid multicast notification of change-of-state events for protection and control applications with high-precision time stamps to support sequence-of-events/first-out analysis.

IEC 61850 Time Synchronizations specifies mappings (1) to Simple Network Time Protocol (SNTP), which can support synchronization down to the 1-2 ms range, and (2) to *IEEE 1588-2008 - IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems*[33], which can support synchronization to the 100 nanosecond range, when implemented with hardware support.

IEC 61850 specifies an Abstract Communication Service Interface (ACSI) with mappings to Manufacturing Message Specification (MMS) protocol, which was developed during the 1980's as part of the Computer Integrated Manufacturing (CIM) movement, as part of the Manufacturing Automation Protocol (MAP) suite. The protocol was originally developed with Programmable Logic Controllers (PLCs) and robotic controllers in mind, but is reapplied by IEC 61850 for use with Intelligent Electronic Devices (IEDs). This protocol provides client/server exchanges for configuring the devices. Mappings are provided for ACSI through MMS to communicate over TCP/IP or over ISO transport.

High Power Electronics Standards

While the world-wide Smart Grid initiative is driving research and development efforts for Microgrids and substation automation, it is also combining with other market forces to drive the research and development of electronic power conversion modules. In conjunction with the Office of Naval Research (ONR), the IEEE Substations Committee recently published *IEEE 1676-2010 - IEEE Guide for Control Architecture for High Power Electronics (1 MW and Greater) Used in Electric Power Transmission and Distribution Systems*[34]. The guide had evolved from work performed by the IEEE Working Group i8 "Power Electronics Building Block Concepts" of the Power Electronics Subcommittee. The effort involved an investigation of several common high-power electronics applications, including:

- Power Quality/Custom Power,
- Flexible AC Transmission Systems (FACTS),
- High Voltage DC Transmission (HVDC),
- Distributed Generation, and
- Energy Storage applications.

The focus was on high power applications ranging from one to several hundred megawatts.
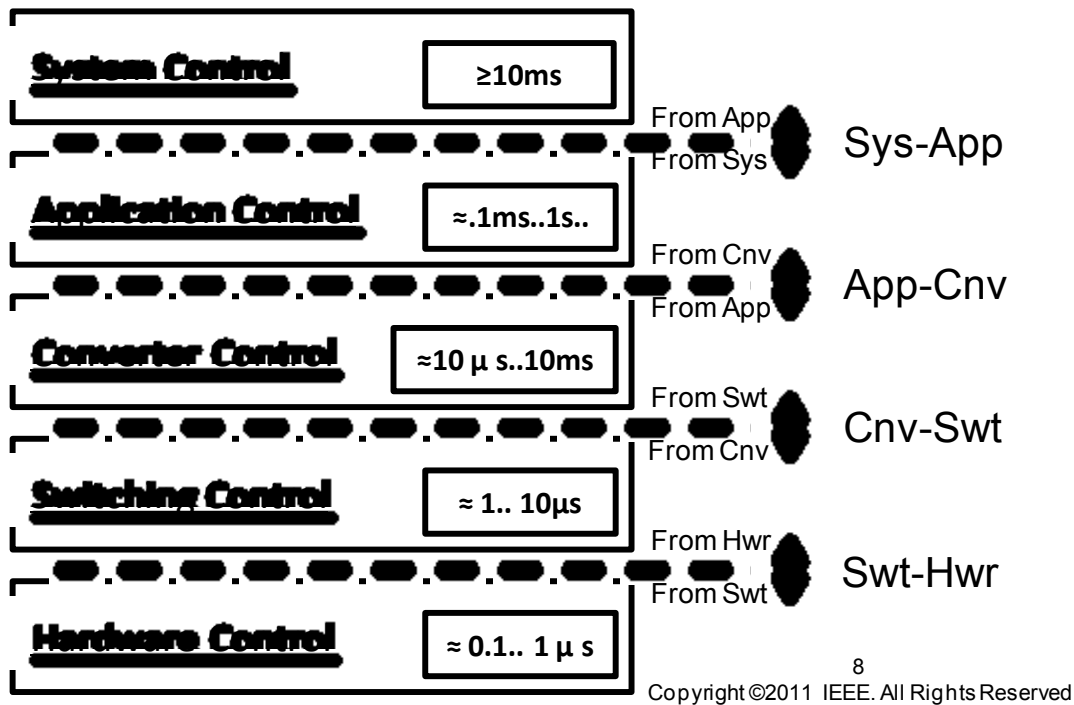
The guide defines a reusable hierarchical control reference architecture, consisting of five layers, necessitated by specific real-time performance requirements, with specific functions performed within each layer and specific parameters exchanged between each set of layers (see Figure 14).

The IEEE's stated intent for the reference model was to enable multiple vendors to design and manufacture components, subassemblies, and software, which could be used in a large variety of power conversion applications. For NGIPS, this reference model provides a preferred framework to support Compact Power development, and to assure continued positive core asset reuse within the commercial power electronics marketplace.

Vision Drivers - Emerging Control System Standards

In addition to the new electrical power system standards emerging from Power System initiatives, several key standards are emerging in control system markets that are important drivers for NGIPS. Traditionally, naval control systems have been based on either embedded control system architectures, like real time operating systems running on single board computers, or on industrial control system architectures, such as commercial Programmable Logic Controller (PLC) systems. Embedded control system architectures have had the advantage of following standards developed for the general purpose computer system industry, and have readily demonstrated the expected advantages of the open architecture approach over time, and further use and development of embedded system standards is strongly encouraged, but a complete discussion of these standards lies outside the scope of this paper.

On the other hand, higher volume, commercial PLC systems have been shown to have lower initial acquisition costs and world-wide logistical advantages over many embedded system components, but at the same time, PLC systems have also been problematic

IEEE Std 1676-2010
IEEE Guide for Control Architecture for High Power Electronics (1MW and Greater)
Used in Electronic Power Transmission and Distribution Systems

Control layer interfaces and signal direction convention

Figure 14: IEEE 1676-2010 Control Layer Reference Model

from an open architecture perspective. Several evolving industrial control system standards are critical for the effective use of PLC systems to ensure application portability and life cycle technology migration and refresh support. Those emerging industrial control standards are:

- *IEC 61131-3 - Programmable controllers - Part 3: Programming languages*[36], which provides language standards for control application programs written for programmable controllers, perhaps better known as Programmable Logic Controllers (PLCs);

- *IEC 61499-1 - Function blocks - Part 1: Architecture*[37], which provides architectural models for the implementation of function block oriented control system applications, and serves as an umbrella standard for actual standard function block libraries like Foundation Fieldbus;

- *IEC 61158 - Industrial communication networks - Fieldbus specifications*[38], which provides specifications for world recognized industrial communication networking standards, and

- *IEC 62541 - OPC Unified Architecture*[39], which

provides a platform-independent standard for control systems integration addressing security, data access, alarms and conditions, control program control and historical data access services.

These evolving international standards provide an initial foundation for a Naval Open Architecture Machinery Control System, but their limitations and lack of maturity are of serious concern, and need to be examined thoroughly.

Programmable Logic Controller Standards

According to industry lore, in 1968 in North America, industrial control manufacturers developed plans for Programmable Logic Controllers (PLCs) in response to a Request for Proposal (RFP) from General Motors (GM) Hydramatic transmission division for a reconfigurable electronic replacement for hard-wired relay control systems. Up to that time, GM's assembly line control systems had been implemented using relay control components designed using standard electrical drawings depicting switches, relay coils, and associated relay contacts. The so-called "Relay Ladder Logic" graphical programming language for PLCs was created to provide

transfer of training for electrical control engineers familiar with relay control systems. For North America, GM was a major market leader, and ladder logic became the preferred language for PLC programming from virtually all manufacturers.

However in Europe, PLCs evolved in several very different ways, leading to other programming languages. In Germany, the first PLC application language was more of a simplified macro assembly language, and in France, additional languages were introduced that represented PLC programs using a higher level simplified PASCAL-like language or as a flow chart (GRAFCET). On the Pacific Rim, ideas were studied and still more variations were developed with similar but different programming languages.

The PLC became quite popular due to its ability to replace relay control systems in factory floor environments. And due its ability to support the online monitoring and modification of control application programs while they were running in real-time. This capability is indispensible when troubleshooting control applications where the process under control cannot be halted and restarted without great effort or cost.

Despite the PLC's success, however, the lack of programming language standards continued to present a large problem. Large end users strongly urged the vendor community to standardize PLC programming languages, and the first major world-wide standardization effort culminated in the introduction of IEC 61131-3[40] (originally IEC 1131). Unfortunately, this broadly embraced initial standard did little to resolve any of the PLC programming language portability issues.

IEC 61131-3 did recognize five distinct programming languages:

- Instruction List (IL), which is similar to macro assembly language for a virtual machine,
- Ladder Diagram (LD), which is the IEC version of relay ladder logic,
- Function Block Diagram (FBD), which is another way to represent programs in a way that is similar to IEC-style drawings of logic gates used in integrated circuit design,
- Structured Text (ST), which is a higher level procedural programming language, and
- Sequential Function Chart (SFC), which is a graphical flow chart representation language with origins in the aforementioned GRAFCET language.

Unfortunately, the IEC 61131-3 standard did not specify language or system function call requirements to the level needed to support application portability. Instead, it introduced the nebulous concept of "Partial-Compliance". The related IEC 61499 standard defines another function block style programming language that is more consistent with the model used by continuous control systems. It also does not ensure portability. A consortium style standards body headquartered in the Netherlands and called PLCopen[41] is trying to develop a truly portable language specification, but its efforts have not influenced the PLC industry leaders to any great extent. PLCopen does appear to have greater traction in motion control segment of the marketplace, where several vendors are adopting its application programming interface requirements.

The IEC 61131-3 standard is also being extended to improve object oriented features of the Structured Text programming language. This effort highlights another area of concern, which is the lack of coherence between IEC 61131-3 and any of the world-wide computer programming language, environment and communication standards, including ADA, C, C++, C#, Fortran, Java, POSIX, POSIX sockets, etc.

The three issues for NOA MCS that may be addressed by IEC 61131-3 over time include:

- The Lack of Language Portability Standards, which is exceptionally poor for the graphical programming languages: IEC 61131-3 LD, FBD and SFC and IEC 61499 FB. Source files for these languages are often kept in proprietary formats with little or no similarities;

- The Lack of System Function Library Standardization (like POSIX, POSIX sockets), especially when accessing diagnostic system functions, time of day clock functions, and network communication functions; and

- The Lack of Integration between PLC Programming Environments and Software Source Control and Configuration Management tools, especially an inability to clearly separate out or export text based source files.

The IEC 61131-3 Structured Text (ST) language seems to offer the most portability at this time, and is directly represented as text, though significant issues still exist within different vendors. In addition, the use of an insulating, platform independent, system function library

is recommended, rather than directly invoking any system function calls directly.

Fieldbus Communication Standards

The evolution of standards for industrial communication technologies is following a familiar pattern that was also seen with the evolution of computer networking technologies. A simplified view of this evolution is presented in Figure 15.
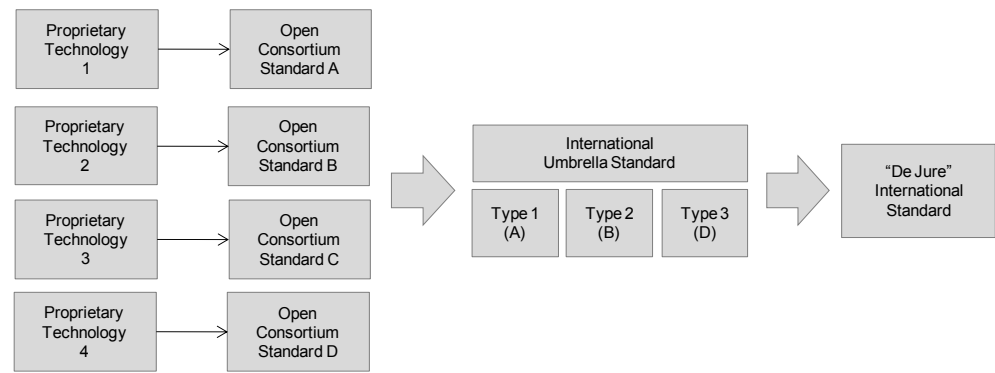

Figure 15: The Evolution of Standards

Initially, several vendors develop competing proprietary technologies during the emergence and proliferation stage of the market. After some period of competition, the cost to end-users of incompatibilities, lock-in and duplication of effort leads them to demand standardization. At the same time, the vendors realize that they must win the standardization effort to survive, so they start forming vendor based consortiums to promote their technology as a standard. At some point after further shakeout, an International Standards Committee reviews the state of the market place and creates an International Umbrella Standard, recognizing and publishing the specifications for the leading technologies. Hopefully, over time and with further shake out, a "De Jure" international standard emerges and migration paths were provided for all the technologies under the umbrella.

A similar evolution occurred during the introduction of computer networking technology. Ethernet, Token Ring, Arc-Net, and many other networking technologies emerged and were competing for market share in the late 1970's and early 1980's. Consortia formed and licensed the network technologies based on published standards for some time, until the IEEE 802 Umbrella standard was written, which identified Ethernet, Token Bus (a

media access control technology developed as part of the Manufacturing Automation Protocol effort, like MMS) and Token Ring as alternative standard implementations[42]. Over time the importance of Token Bus and Token Ring has eroded, Ethernet became the "De Jure" standard, and IEEE 802 was expanded to include many new Ethernet compatible technologies.

Similarly, *IEC 61158 - Industrial communication networks - Fieldbus specifications*[43] is the umbrella standard for control system communications (see Figure 16).

But unlike IEEE 802, which specified only three

Figure 16: IEC 61158 as an Umbrella Standard

alternative technologies, IEC 61158 has included 16 Communication Protocol Families (CPFs), though one has been dropped over time.

A detailed summary of the IEC 61158-2008 CPFs is presented in Figure 17. One reason why there are so many CPFs specified is that the market has traditionally been composed of five independent segments, as shown in the five columns in the figure, and many of the CPFs are more regional, including North American, European, and Pacific Rim standards.

IEC 61158-2008 Communication Protocol Family (CPF)	Industrial Communication/Fieldbus Application Segment				
	Control Networks	Intelligent Industrial Devices	Basic Industrial Devices (Switches/Buttons)	Process Transmitters/Smart Transmitters	Coordinated Drive Controls/Motion Controls/CNCs
CPF 1 - Foundation Fieldbus (Emerson)	Foundation Fieldbus HSE			Foundation Fieldbus H1/H2, SP50	
CPF 2 - Control and Information Protocol (CIP) (Rockwell)	ControlNet, Ethernet/IP		DeviceNet		ControlNet
CPF 3 - Profibus (Siemens)	Profibus DP, Profinet	Profibus DP		Profibus PA	Profinet
CPF 4 - P-NET	P-NET RS232/485, P-NET on IP	P-NET RS232			
CPF 5 - WorldFIP				WorldFIP	
CPF 6 - InterBus (Phoenix Contact)	InterBus-S	InterBus-S	InterBus-S		
CPF 7 – Swifnet					
CPF 8 - CC-Link (Mitsubishi)	CC-Link IE Control, CC Link IE Field, CC-Link, CC Link LT, CC-Link Safety				
CPF 9 - HART				HART	
CPF 10 - Vnet/IP (Yokogawa)	Vnet/IP				Vnet/IP
CPF 11 - Tcnet (Toshiba)	TCnet				TCnet
CPF 12 - EtherCAT (ABB)	EtherCAT				EtherCAT
CPF 13 - Ethernet Powerlink/ CANopen	Ethernet POWERLINK (EPL)				Ethernet POWERLINK (EPL)
CPF 14- Ethernet for Plant Automation (EPA, Kyland/ China)	Eternet for Plant Automation (EPA)				
CPF 15 - Modbus-RTPS	Modbus-TCP, Modbus-RTPS (DDS)	Modbus, Modbus-TCP			
CPF Number 16 - SERCOS					SERCOS I, II, III

Figure 17: IEC 61158 Communication Protocol Family Summary

Though many of the technologies compete for the control network segment, only a few compete in the more specialized segments. Within the control network segment, there has been a consolidation toward switched Ethernet based technologies, however, there has been little shakeout among the competing Ethernet protocols, and several technologies have introduced extensions to Ethernet to improve determinism and jitter performance. These technologies may also be affected by the high availability PRP and HSR networking technologies emerging from substation automation. For the control networking segment, it is best to not become too dependent on any of these specific protocols, and to try to use standard Ethernet technology whenever possible.

The second column highlights the market for intelligent industrial devices, such as a motor controller, where multi-drop serial interfacing, using the RS-485 or RS-422 electrical standards is still more cost effective then Ethernet technologies. For this application, Profibus-DP and Modbus are the leading technologies that are commonly used in machinery control systems.

The third column highlights communication technologies that were developed for very low cost basic industrial devices, typically as a multi-drop replacement for digital wiring. These technologies may be of interest for some design issues, but have not played a major role in naval machinery control, to date. The last two columns cover process transmitter networks, focusing on upgrading existing 4-20ma infrastructure, and coordinated drive networks, where fast, low jitter communications were critical for multi-axis motion control and paper and fiber web processes.

System Interfacing Standards

Prior to the advent of Personal Computers (PCs), Human Machine Interface (HMI) systems were typically integrated into control systems using proprietary technologies provided the control system vendor. These took the form of operator consoles, for process control systems, or panel mounted displays, for machine builders or assembly line systems. The underlying technologies usually were licensed from general purpose computer manufacturers or were based on the control system vendor's proprietary microprocessor systems.

With the advent of the PC, a new product market formed the PC HMI market. These products provided distributed control system capabilities at a lower price point, when used in conjunction with Programmable Logic Controllers (PLCs). Unfortunately, these products depended on a myriad of proprietary communication technologies and protocols (the protocols identified in IEC 61158 barely scratch the surface), and the burden of developing these communication interfaces fell to the

PC HMI company. Later, process control system vendors began to port their proprietary HMI systems to personal computer platforms, and they also desired a standard way to communicate to the wide of variety of third party devices that might be encountered in the typical process control environment.

In 1995, Microsoft began encouraging the development of vertical market Application Programming Interface (API) standards based on their Component Object Model (COM) and Object Linking and Embedding (OLE) technologies. With Microsoft's help, an industry task force was assembled to prototype a set of standard APIs for control system integration. The group later became known as the OLE for Process Control task force, or simply the OPC task force. The task force delivered its first interface standard, OPC Data Access Version 1, covering server discovery and rendezvous, server security, data item browsing, and publish and subscribe data access capabilities in 1996, when the effort shifted to marketing and sustaining the activity.

The group formed the OPC Foundation, which sold corporate and end-user memberships, and expanded the scope of its standard APIs to cover alarms and conditions and historical data access. The foundation also developed compliance and interoperability test tools and sponsored interoperability testing events. The OPC APIs became widely adopted world, and have been a great success for both the PC HMI and process control system markets. The OPC Foundation also started initiatives aimed at data access across Intranets or the Internet.

The primary benefit of the OPC APIs was to shift the burden of development of the communications drivers from the PC HMI product teams, back to the control system product vendors. Prior to this shift, every PC HMI product frequently required updates every time the control system product vendor introduced a new product or communications variant. After OPC, the control system vendor was responsible for updating their OPC server as part of the control system product update.

Though the OPC APIs were highly successful, they were tied to Microsoft's proprietary underlying COM technology, which limited their applicability, and when Microsoft decided to create their new .NET Common Language Runtime technology, updates were needed for the COM based OPC APIs to extend their applicability. The technical subcommittees within the OPC Foundation developed a new vision for a next generation OPC, which they later called OPC Unified Architecture. Key drivers of the vision were:

- To build on the success of the OPC APIs, but to unify the data access, alarms and conditions, and historical data access interfaces into a common and consistent server address space;

- To eliminate the dependency of OPC on proprietary Microsoft technology, by focusing on open standard communication mechanisms;

- To provide mechanisms that would extend OPC's reach from the personal computer environment to both embedded systems and internet applications.

In addition, they strove to make OPC Unified Architecture a true international standard. The result of this effort is *IEC 62541 - OPC Unified Architecture*[46], as summarized in Figure 18.

The standard includes an extended security and communications model, which supports unified versions of the familiar OPC service domains: server discovery and rendezvous, item browsing, data access, alarms and conditions, program control and historical data access.

The extended security model supports optional public/private key payload signing using the Public Key Infrastructure (PKI) and AES (Advanced Encryption Standard) payload encryption. Requests can be encoded in a compact binary format, for embedded systems, or in a platform independent XML (eXtensible Markup Language) format, for web-based systems. Also, the communications can be based on TCP (Transmission Control Protocol) for embedded systems, or on SOAP (Simple Object Access Protocol) XML posted over HTTP or HTTPS (Hyper-Text Transport Protocol or Secure Hyper-Text Transport Protocol) for web-based systems. The OPC Foundation has also provided compliance testing tools and interoperability workshops, building momentum from their previous successes. The OPC Foundation also provides members with a reference implementation of the protocol stack, and through the foundation and its tool making members, stacks are available for ANSI 'C', ANSI C++, C#, VB.NET and Java.

There are two notable performance deficiencies in OPC Unified Architecture that impact NOA MCS for NGIPS. First, the OPC UA always communicates over client/server sessions, so server communication loads are not invariant with the number of clients, as they would be with an isochronous multicast model. Second, the new OPC standard does not support in-process servers. The original COM based technology supported in-process servers that could serve as a minimal wrapping
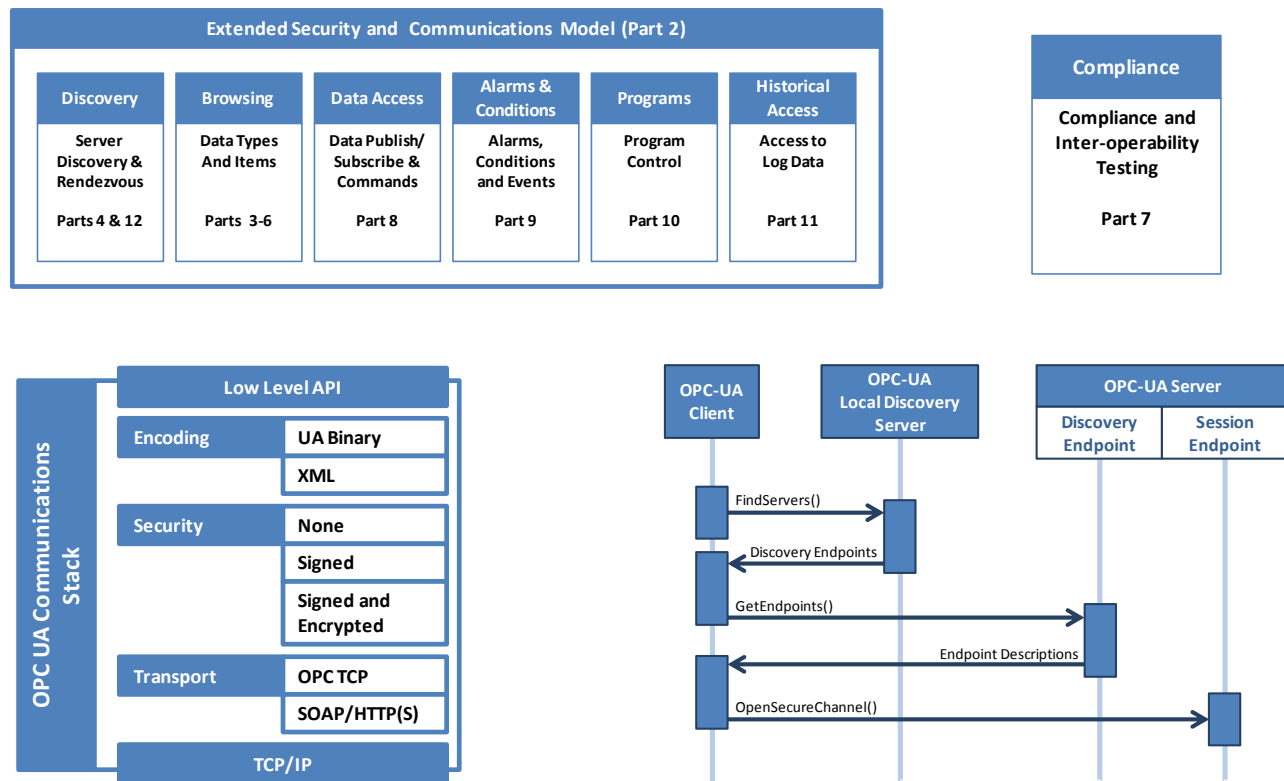
Figure 18: IEC 62541 - OPC Unified Architecture Overview

layer that could take advantage of underlying multicast transport. As a result of these deficiencies, OPC UA cannot be widely prescribed without a careful analysis of its impact on performance requirements.

NOA Machinery Control Systems - A Straw-Man Vision

So finally, we return to our initial goal, to establish and share a detailed architectural vision for an outstanding Naval Open Architecture (NOA) Machinery Control System (MCS). In getting here, we have reviewed naval guidance concerning best practices and established the need for a modular open systems architecture system based on key interface standards that ensure modular independence and upgradability. We have also reviewed relevant international standards for electrical power systems, high power electronic converters, and control systems to determine their applicability to NOA MCS, with special emphasis on areas relevant Next Generation Integrated Power System (NGIPS).

Furthermore, we have also discussed the importance of MCS reuse based on a multiple application segment product line acquisition strategy and the use of commonality based ship design. So how should we

structure this product line strategy, and what product goals should we define?

Product Line Over-Arching Directions

First, we must answer the two questions posed earlier in the paper: "What should the long term role be for the Navy?" and "What should the long term role be for the suppliers?" As an initial consideration, we must review how Navy MCS projects typically unfold, as part of a "Navy After Next" class development, or part of "Next Navy" flight improvement, or part of a "Current Navy" modernization. Figure 19 depicts two sequential Navy MCS projects, contracted to two different Integrated Project Teams, perhaps working on the same or different ship classes, but the figure is meant to be even more thought provoking than just this.

There actually are many ways the work on any given project can be subdivided and contracted even within the development cycle. Perhaps requirements engineering and system design is to be performed by one team, and software architectural design and development is to be done by another, while systems verification and test is to be done by yet another. Given this, and many other potential arrangements, how do both the Navy and its
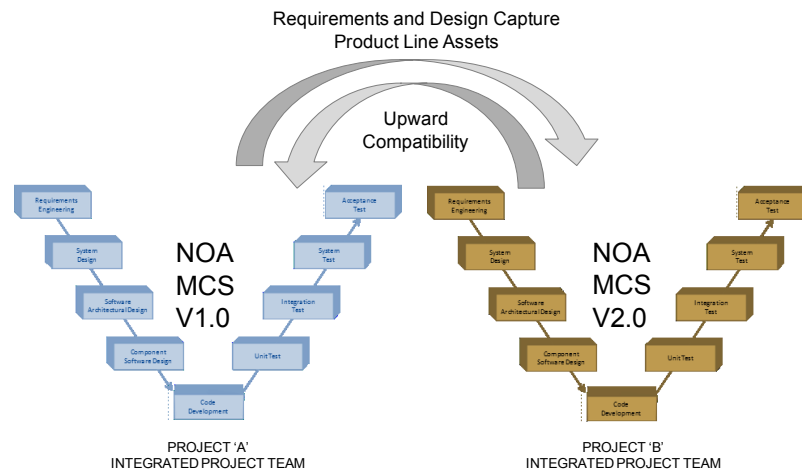
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Figure 19: Applying the Product Line Approach in the Real World

suppliers develop core assets and product lines that are engineered for reuse, that are transferable between MCS efforts, and that can offer upward compatibility for the future modernization of past efforts based on the same product line?

The Navy's product line vision must leverage its core competencies and assets, while the business community's product line vision must leverage theirs. For the Navy, this seems to mean an increased focus on more prescriptive and reusable core assets and products for:

- Machinery Control System Specification and Standardization,
- Machinery Control System Product and Application Segment Requirements,
- Machinery Control System Interface Designs, and
- Machinery Control System Verification and Validation Testing.

The vision is for the Navy to collaborate with its suppliers, through cooperative R&D to demonstrate "proof of concept" solutions and by encouraging Original Equipment Manufacturers (OEMs) to sign on by providing access to specifications and draft code.

Pursuant to this goal, the Navy's product line might include segment specific libraries of portable core assets for:

- Standards Based System Data Formats,
- Standards Based Interface Specification Formats,
- Standards Based Display System Components and Systems,
- Standards Based Control Application Components and Systems, and

- Standards Based Data Repository and Report Formats.

In short, the Navy's product line should focus on providing reusable MCS application assets with increasing quality control, lower per project Non-Recurring Engineering (NRE), and increasing levels of commonality-based MCS design.

At the same time the business community should focus on providing a scalable and configurable, high performance, portable, software-based NOA MCS platform:

- That can integrate the Navy's reusable standards-based product libraries for displays, controls, subsystem interface specifications, data repositories and reports,
- That can run on Navy's Commonality-based MCS hardware modules,
- That can interface with standard industrial networks and field buses,
- That has a modular open systems architecture with clear interfaces to support extension and integration, and
- That is based on key best practices, and supports emerging standards and technologies.

In short, the business community should focus on providing a world-class modular open MCS platform that can support standards-based portable Navy product assets.

Applying the Vision to NGIPS

The general product line vision for Naval Open Architecture Machinery Control Systems (NOA MCS) provides a clearer long term goal for machinery control,
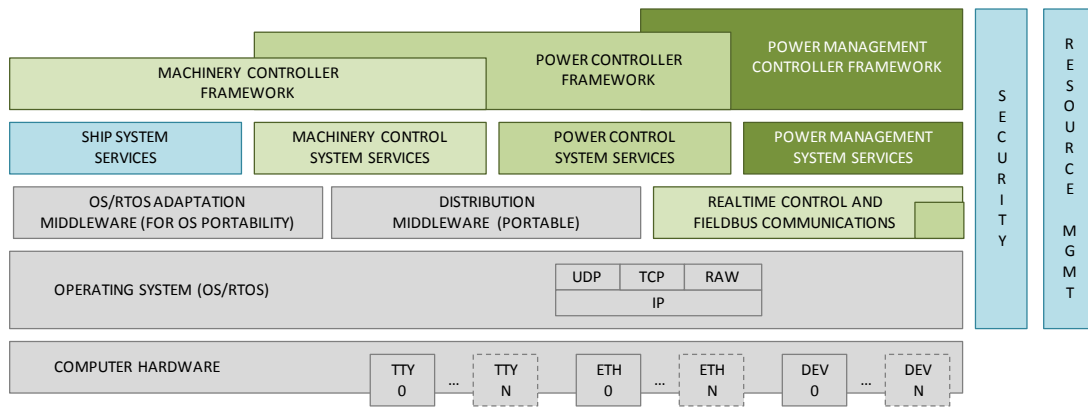
Figure 20: Proposed NOA MCS Framework for NGIPS

in general, but how does it apply to the very challenging goal of Next Generation Integration Power Systems (NGIPSs), where emerging standards and technologies must be embraced and applied? The proposed NOA MCS framework shown in the figure provides a foundation for NGIPS (see Figure 20).

Ideally, the foundation for this effort would be fully in place, and the framework for NGIPS functionality would be able to leverage the mature, NOA MCS framework. In addition, there is a concurrent push to improve information assurance that must be accommodated. So in reality, the concurrent developments of NGIPS and NOA MCS may require NGIPS component suppliers to implement their own frameworks in conjunction with interim NOA MCS solutions.

In a way that is similar to the substation communications design for IEC 61850, the control modules involved in the NGIPS may have to rapidly and reliably share real-time reconfiguration and fault detection information, and respond to it in very short periods of time, and these special performance requirements may be beyond the reach of the general purpose NOA MCS data access protocols. If this is the case, NGIPS may require its own communication services.
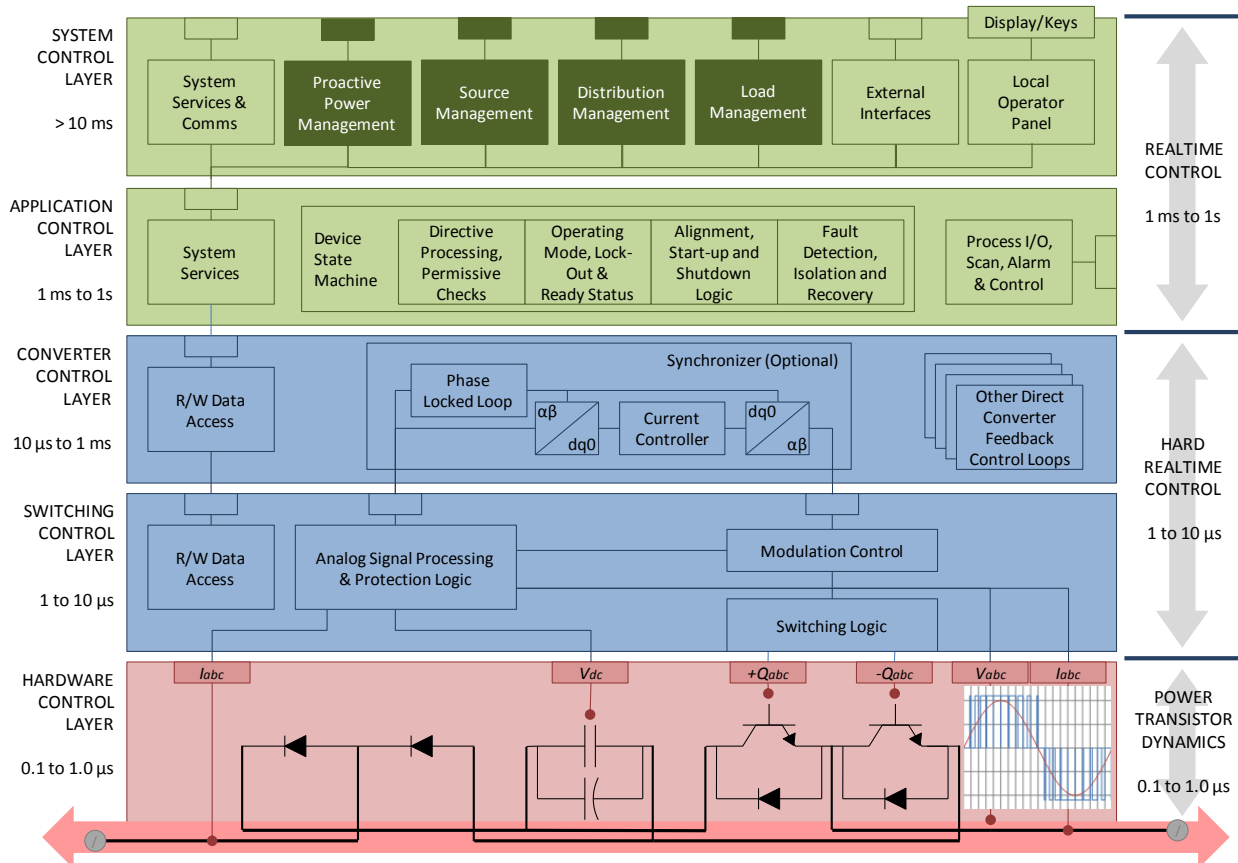

Figure 21: Power Conversion Module Reference Architecture Based on IEEE 1676-2010

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Additionally, these NGIPS communication services may be logically broken up into (1) controller services needed for protection, fault detection and isolation, and fault recovery, and (2) more proactive control power management communication services, orchestrating temporary reconfigurations to support specific mission objectives. Splitting up the design of these services to define specific subsets needed for specific classes of devices may be advantageous.

The general point is that the NOA MCS framework should not prevent and indeed should support the addition of dedicated high performance communication services, when needed. Of course, these new services should also be defined with published open formats, to allow collaboration in the supplier community.

Power Conversion Module Architectures

With regards to IEEE 1676-2010 High Power Electronics reference design, the general purpose NOA MCS architecture should apply to the application and system control layers, as illustrated in Figure 21. The diagram makes a distinction between (1) the real-time control regime, which can generally be achieved using general purpose microprocessors and a multitasking real-time operating system, and (2) the hard real-time regime, which generally requires dedicated microprocessors or digital signal processors (DSPs) operating over a known instruction path length in a hard loop with very limited external interaction.

The application layer would generally be involved with converter alignment, directive processing and fault detection, isolation and recovery. It would also interface with I/O devices not directly interfaced to the switching control layer, including circuit breakers used for converter alignment and isolation, for instance.

The system layer would interface with the NOA MCS control network, where it should participate with the NOA MCS service layers, providing diagnostics, publishing data, receiving directives, and publishing alarms and events. In addition, the system layer would interface with any NGIPS specific distributed communication services. Power conversion modules may be involved in power source management, when they used to convert power from generator source power levels to distribution levels, or they may be involved in distribution management, when they are integrated with circuit breakers that are involved in power distribution alignment and serve the roles of both a PCM and PDM, or they may be involved in load management, when they serve the role of a variable speed drive. In addition, the converter may participate in proactive power management, performing an orchestrated role in a mission specific activity.
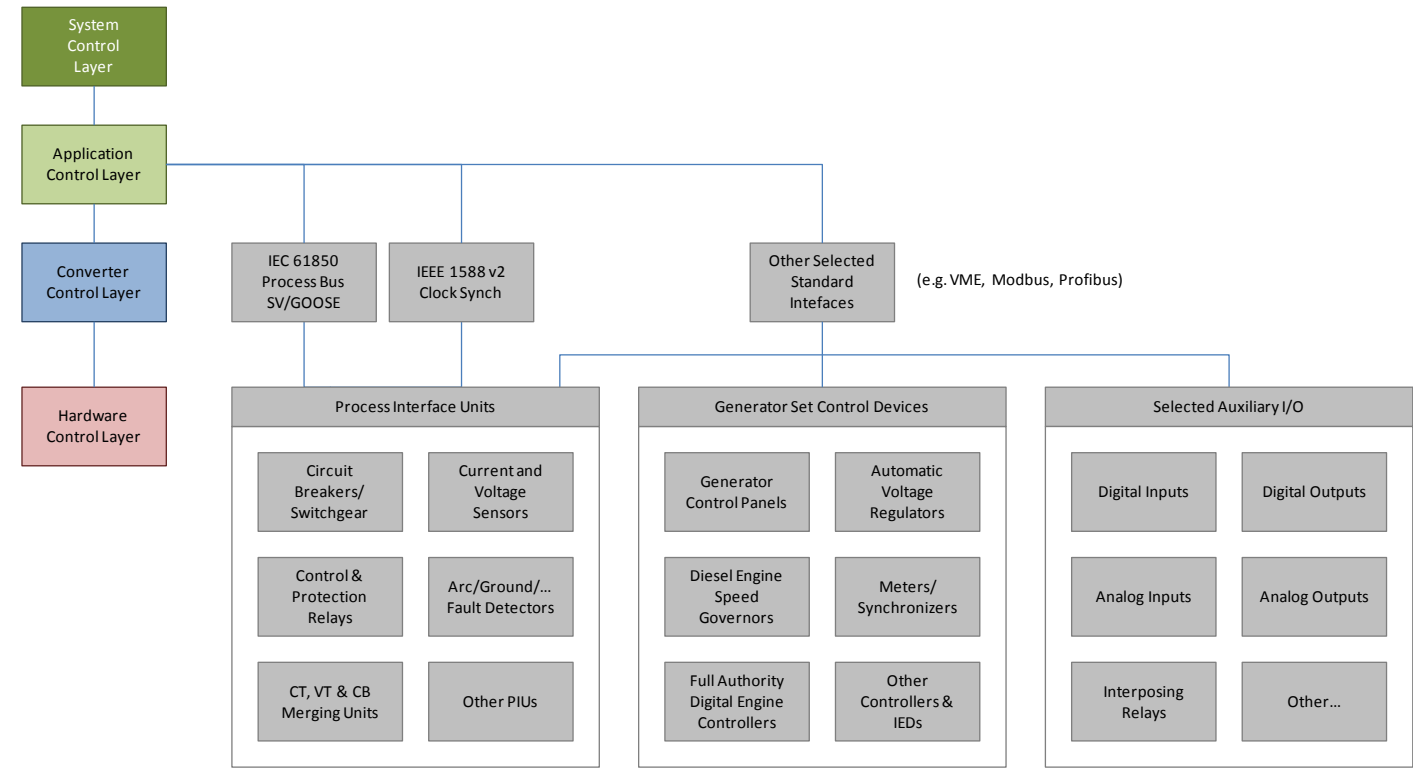

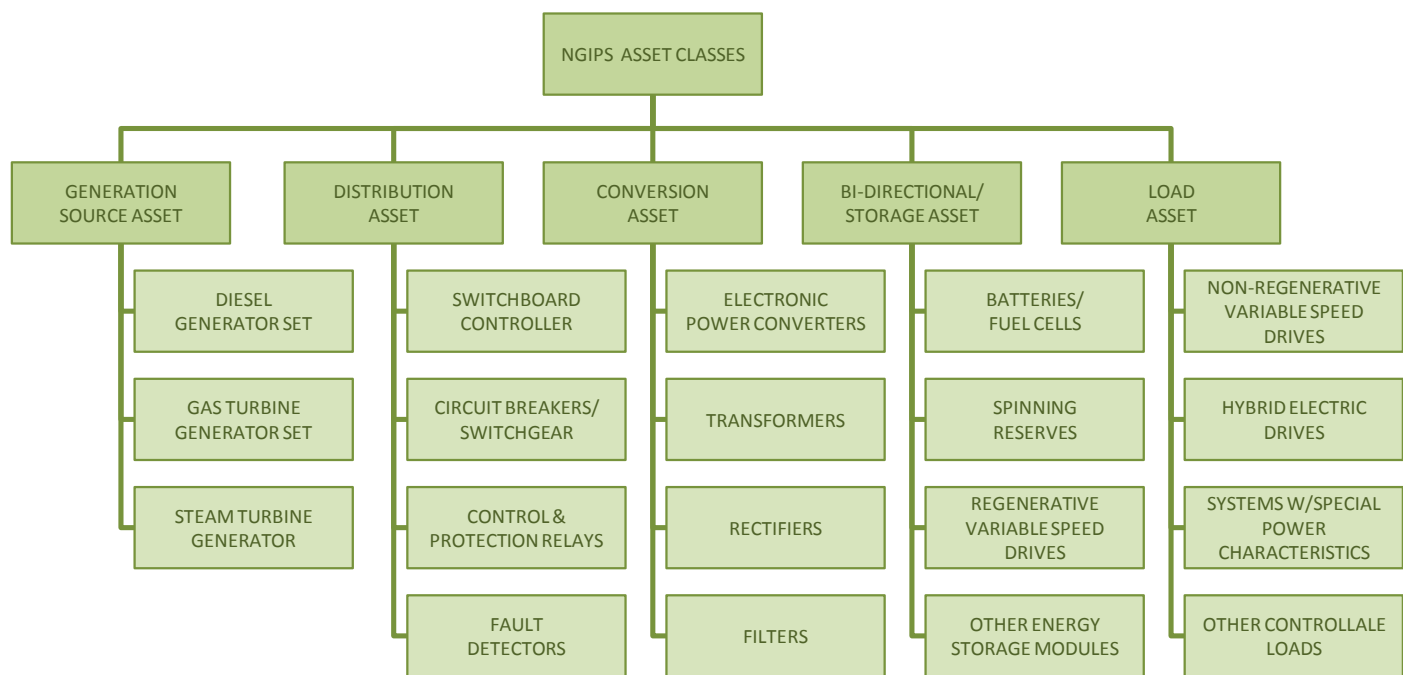Figure 22: Power Conversion Module External Interface Requirements

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Figure 23: NGIPS Asset Classes

A reusable NGIPS controller framework should support communications from the application layer to support multiple roles within the system including those involving power conversion and those that don't (such as a switchboard controller acting as a power distribution module). The various types of I/O and external communication that this framework should support are summarized in Figure 22.

Looking forward, the system should incorporate the ability to interface to a wide variety of devices using the emerging IEC 61850 Process Bus, but looking backward, the system will most likely still have to support common legacy interfaces, including digital signals and serial communications (e.g. Modbus or Profibus).

The expected benefits of IEC 61850 Process Bus solutions for substation automation may not directly translate to advantages for NGIPS modules, where the elimination of copper control relay wiring may not be a major cost driver, given the higher levels of Non-Recurring Engineering (NRE) associated with NGIPS modules. However, the innovation among product vendors in this market will likely provide benefits to NGIPS over time.

Key opportunities currently appear to be:

- The ability to support multiple current and voltage transformer signals using one set of signal analysis

and synchronization electronics.

- The ability to implement advanced protection schemes incorporating wave form input symptoms from multiple sources.

- The ability to provide enhanced wave form awareness, analysis and capture for post-mortem fault and excursion analysis.

In addition, product vendors supporting the world-wide electric power industry appear to be "all-in" from a research and development perspective, when it comes to future products and IEC 61850.

Distributed Power Management Control

For the purposes of system level NGIPS functions, system components will be separated into five asset classes, as illustrated in Figure 23.

Each asset class will support an abstract asset-class specific system interface design, to support monitoring and control of the asset. Some NGIPS power conversion modules will serve as multiple distinct assets at the system level (for instance, a distribution asset and a conversion asset).

The source management activity, involves the selection, alignment and change-over of power generation source assets, including generator sets, emergency generator sets, and shore power connections. Alignment may
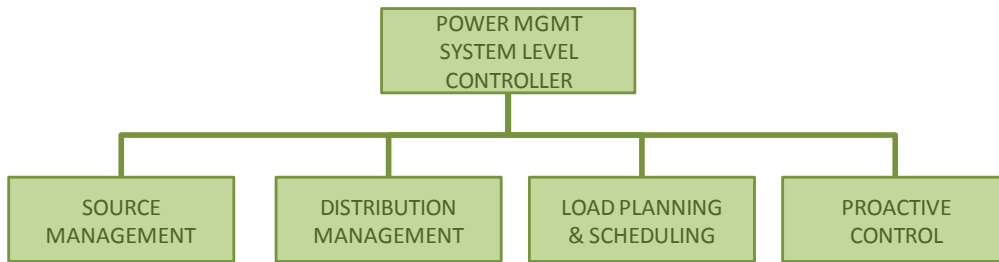
Figure 24: Power Management System Level Controller Functions

include power reserve levels, and automatic start sequencing set points.

The distribution management activity would primary involve the selection, alignment, change-over and fault isolation and recovery strategy alignments of power distribution and some power conversion assets.

Load planning and scheduling would involve the alignment and orchestration of smart ship loads to accomplish objectives to support mission specific power requirements. These activities would primarily interact with bi-directional and load assets.

Proactive control, may involve the orchestration of many NGIPS assets to ensure the availability of resources to support mission specific objectives.

It may be instructive to map this system level power management view of NGIPS to a more familiar electric plant one-line diagram, as shown in Figure 25.

Each of the major components of the one-line diagram on the left has been labeled with its associated asset class. The one-line diagram depicts an integrated power system with two propulsion motors directly connected to the two primary switchboards, and a zonal electrical
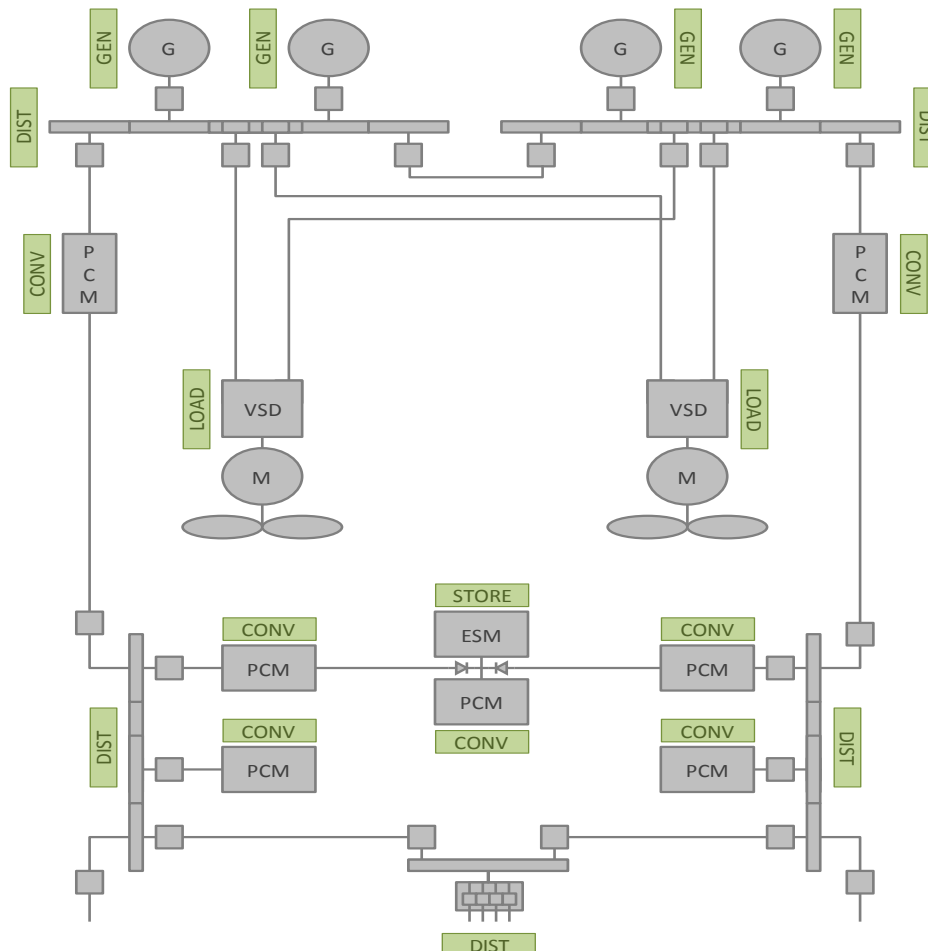

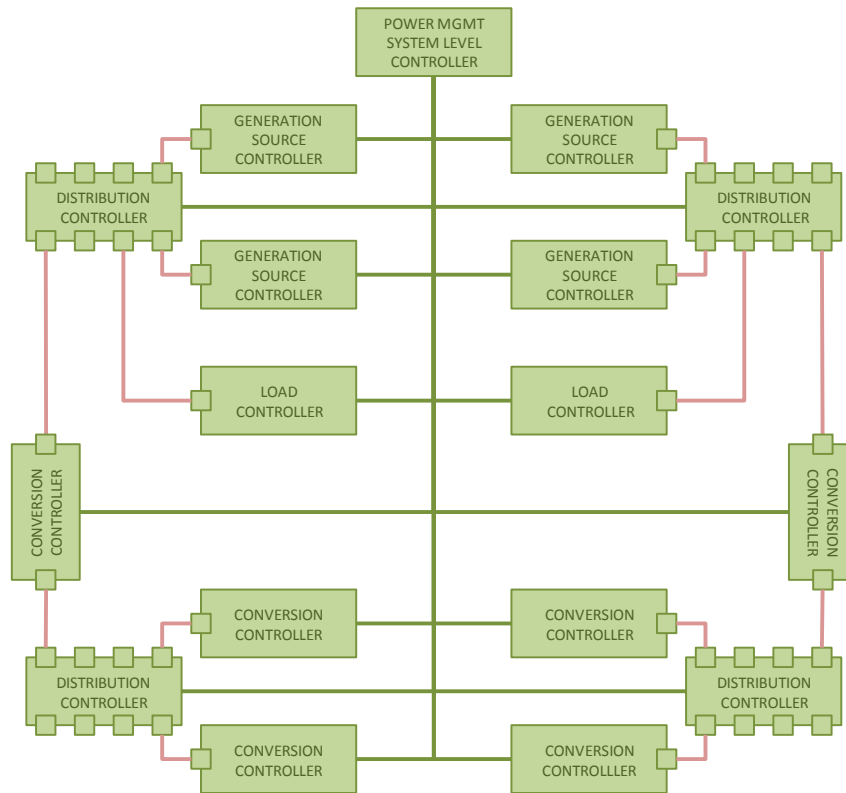Figure 25: Mapping Power Management to a One-Line View

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Figure 26: Mapping Power Management to an Asset Class View

distribution system, but depicts only one zone, which includes a shore power connection.

A corresponding asset class view of the same one-line diagram is shown in Figure 26. The control plane connections are shown in green while some of the power plane connections are shown in red. With this more familiar one-line view, source management, distribution management and load planning and scheduling might seem more clear, and it becomes more apparent how the tightly interconnected NGIPS components on the power plane must form a tightly interconnected, fault tolerant distributed control system on the control plane.

The definition of NGIPS asset classes and the attempt to develop asset class specific interfaces represents one of the key ways in which the plant is being engineered for reuse with a product line strategy. The goal is to be able to reuse asset class drivers between projects, along with most of the core controller modules used to implement power distribution and power conversion modules.

The higher level, system control may be ship class design dependent, but at least the communications design can be reused between ship classes, and efforts can be focused on the changes in the power generation, distribution and load center networks.

Conclusions and Next Steps

This paper presented a detailed straw man architectural vision for the development of Naval Open Architecture (NOA) Machinery Control Systems (MCSs) with a special emphasis on the requirements of Next Generation Integrated Power Systems (NGIPSs). A key strategy employed in this vision was the use of a product line acquisition approach, and a careful separation of roles between the Navy and the supplier business community. A large set of applicable standards was reviewed, and used to develop aspects of this vision.

Several specific Navy product line deliverables were discussed, and key requirements of NOA MCS platforms were established. These deliverables included:

- Reusable Control Application Components and Specifications;
- Reusable Display Application Components and Specifications;
- A Standard Reusable Control Application Database Format; and
- Reusable Data Repository and Report Formats and Specifications.

These deliverables and requirements were presented as a "Straw Man", hoping to facilitate more discussion and critical feedback, in an effort to improve the ideas and arrive at a much stronger architectural vision down the

road. The next logical step is to start this critical review process, and to use it to establish a strong shared vision, and to evaluate incentives for achieving this vision, to support activity planning.

There are many projected areas of cost savings and quality improvements that should arise from this effort. In the area of cost savings, there should be:

- Improved requirements reuse and transmission leading to reduced MCS project rework;
- Decreased MCS per project Non-Recurring Engineering (NRE) due to increased product line reuse;
- Increased commonality-based design, increasing reuse of logistics-off-the-shelf modules and reducing life-cycle acquisition and integrated logistics support costs;
- Increased adaptation of MIL-SPECs to be containers of emerging commercial specifications and standards, retiring dependence on specialty manufacturing of components; and
- Increased opportunities for rationalization of systems and cost reductions associated with the carrier/surface combatant/submarine specification divide.

In the area of quality improvements, there should be:

- Evolving requirements capture and reuse, leading to higher quality implementations;
- Evolving MCS applications and platforms, leading to higher quality implementations; and
- Improved sailor and engineering transfer-of-training between machinery control systems, leading to more focused proficiency and ability to perform.

After strengthening this shared vision and further evaluating incentives, the remaining steps of the strategic planning process can be followed: (1) performing an assessment of the current situation, (2) contrasting the current situation with the vision to identify key gaps, and finally, (3) to combine these gaps with ongoing project activities to define a detailed road map that can advance us toward our shared vision.

As an immediate next step in advancing this vision, the Naval Sea System Command (NAVSEA) has issued a Request for Information (RFI) on behalf of PMS 320 Electric Ships Office (ESO), seeking information from industry to assist in updating the Next Generation Integrated Power System (NGIPS) Technology Development Roadmap issued in November 2007. The updated road map will reflect potential back fit applications as well as the Navy's current shipbuilding plan.

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